EFFECTS OF DEICING SALTS ON THE DURABILITY OF CONCRETE INCORPORATING SUPPLEMENTARY CEMENTITIOUS MATERIALS

By
Ali Abdul Baki
David Darwin
Matthew O'Reilly

A Report on Research Sponsored by

THE STRUCTURAL ENGINEERING AND MATERIALS LABORATORY OF THE UNIVERSITY OF KANSAS

Structural Engineering and Engineering Materials
SM Report No. 140
May 2020

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

KU

EFFECTS OF DEICING SALTS ON THE DURABILITY OF CONCRETE INCORPORATING SUPPLEMENTARY CEMENTITIOUS MATERIALS

By

Ali Abdul Baki

David Darwin

Matthew O'Reilly

A Report on Research Sponsored by

THE STRUCTURAL ENGINEERING AND MATERIALS LABORATORY OF THE UNIVERSITY OF KANSAS

Structural Engineering and Engineering Materials

SM Report No. 140

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.

LAWRENCE, KANSAS

May 2020

ABSTRACT

The durability of concrete mixtures incorporating one of two supplementary cementitious materials (SCMs), slag cement or Class C fly ash, exposed to sodium chloride (NaCl), calcium chloride ($CaCl_2$), or magnesium chloride ($MgCl_2$) is evaluated based on damage due to wetting and drying and scaling, with the goal of determining appropriate replacement levels of portland cement using these SCMs. The mixtures had water-to-cementitious material ratios of 0.38 and 0.44 and SCM percentage replacements of portland cement of 0%, 20%, 35%, and 50% by volume. Fourteen concrete mixtures (204 specimens) were cast to evaluate the damage to concrete subjected to 300 cycles of wetting and drying while exposed to solutions of one of the three deicing salts or deionized water in which the temperature of the specimens ranged from 39.2 ºF (4 ºC) during the wetting cycle to 73 ± 3 ºF (23 ± 2 ºC) during the drying cycle. Of special interest were the effects of $CaCl_2$ and $MgCl_2$, which result in the formation of calcium oxychloride. Durability was evaluated based on the average relative dynamic modulus of elasticity and the nature of physical damage, if any. Mixtures subjected to $CaCl_2$ or $MgCl_2$ that exhibit no spalling at test completion are considered to be durable. Ten concrete mixtures (156 specimens) were cast with curing periods of 14 or 28 days to investigate scaling over 56 cycles in accordance with Quebec test BNQ NQ 2621-900 using NaCl or $CaCl_2$. Mixtures are considered durable if the average cumulative mass losses are less than the BNQ NQ 2621-900 failure limit of 0.10 lb/ft^2.

The results show that wetting and drying with deionized water or an NaCl solution does not cause deterioration of concrete. Exposure to $CaCl_2$ and $MgCl_2$, however, both of which result in the formation of calcium oxychloride, causes physical damage and a reduction in the dynamic modulus of concrete with portland cement as the only binder, with $CaCl_2$ being the more deleterious of the two. A partial replacement of portland cement with either slag cement or Class

C fly ash is effective in producing durable concrete exposed to $CaCl_2$ or $MgCl_2$. Using a 20% replacement of portland cement with an SCM, however, is not sufficient to produce durable concrete under conditions that result in the formation of calcium oxychloride, while replacing 35% or 50% of the portland cement with one of the SCMs used in this study is. The results, also, show that using slag cement or Class C fly ash as a replacement of portland cement results in an increase in scaling compared to concrete with portland cement as the only binder. For mixtures with portland cement as the only binder and with a 20% slag cement replacement of portland cement, $CaCl_2$ causes somewhat more scaling than NaCl. For mixtures with a replacement percentage using either SCM of 35%, NaCl causes more scaling than $CaCl_2$. In all cases, however, the scaling mass losses for mixtures with 35% SCM replacements of portland cement were below the BNQ NQ 2621-900 failure limit. At 50% volume replacements, the increase in scaling is noticeably higher than with 20% and 35% replacements, especially for mixtures exposed to NaCl. The mass losses for mixtures with a 50% SCM replacement of portland cement exposed to NaCl exceeded the BNQ NQ 2621-900 failure limit. Extending the curing period from 14 to 28 days has no measurable effect on the scaling for most concrete mixtures in the study.

Based on the findings of the wetting and drying and scaling tests, a partial replacement of portland cement with either slag cement or Class C fly ash is essential to produce durable concrete that will be subjected to the deicing salts $CaCl_2$ or $MgCl_2$ that cause the formation of calcium oxychloride. Using a 20% volume replacement of portland cement is not adequate, while a 35% volume replacement is. Replacement percentages above 35%, however, are not recommended when the deicing salt NaCl may be used because of increasingly poor scaling resistance with increasing slag cement and Class C fly ash replacement levels.

Keywords: calcium oxychloride, concrete, durability, dynamic modulus of elasticity, fly ash, mass loss, replacement percentage, scaling resistance, slag cement, wetting and drying cycles

ACKNOWLEDGEMENTS

This report is based on a thesis presented by Ali Abdul Baki in partial fulfillment of the requirements for the Ph.D. degree from the University of Kansas. Support was provided by the Structural Engineering and Materials Laboratory of the University of Kansas and the Iraqi Government.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 - INTRODUCTION

1.1 GENERAL

Although concrete is widely used for constructing bridge decks and pavements, it is susceptible to deterioration due to freeze-thaw damage, salt scaling, chemical reactions with deicing salts, cracking, alkali-aggregate reactions, and corrosion of steel reinforcing bars. Rehabilitation of deteriorated concrete in bridge decks and pavements is a financial challenge; recent studies have placed the cost of rehabilitation of bridges in the U.S. at $123 billion (ASCE 2017). Because of this cost, many studies have been conducted to identify technologies that can improve the durability of concrete, defined as concrete's ability to maintain its original properties, shape, and quality when exposed to the environment (ACI Committee 201.2R-16). Among them, the University of Kansas (KU) has established specifications for low-cracking high-performance concrete (LC-HPC) bridge decks (Lindquist, Darwin, and Browning 2008, McLeod, Darwin, and Browning 2009, Yuan, Darwin, and Browning 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018). These specifications were developed based on knowledge of good construction procedures, laboratory tests, and field surveys of bridge decks and provide a technical methodology for design and construction. This methodology includes material selection, mixture proportioning, environmental considerations, consolidation, finishing, and curing of concrete. In the initial specifications, only portland cement was recommended for use as a cementitious material. There is a significant need, however, to investigate the effects of using supplementary cementitious materials (SCMs), such as slag cement, fly ash (FA), and silica fume, as a partial replacement of portland cement and establish a range of percentage replacements of cement with SCMs for bridge decks and pavements.

Before this investigation can take place though, it is necessary to address the challenge faced when deicing salts react with concrete. The reaction between calcium hydroxide ($Ca(OH)_2$), which is formed during hydration of portland cement, and deicing salts, specifically calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$), can cause damage to concrete due to the formation of calcium oxychloride ($CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_20$), which is expansive, undergoes phase changes with changes in temperature, and causes deterioration, especially at cracks and joints where deicing chemicals have easy access to the concrete (Farnam et al. 2015a, Farnam et al. 2015b, Qiao, Suraneni, and Weiss 2017).

Fortunately, using SCMs can combat this issue. Recent studies have found that replacing portland cement with SCMs reduces the formation of both calcium hydroxide and calcium oxychloride (Jain et al. 2012, Suraneni et al. 2016, Ghazy and Bassuoni 2017). Additionally, using SCMs as a partial replacement for portland cement improves the durability of concrete by controlling the alkali-silica reaction, improving sulfate resistance, reducing leaching and efflorescence, and decreasing chloride penetration (Mindess, Young, and Darwin 2003).

Other studies have found, however, that using SCMs as a partial replacement of portland cement reduces the scaling resistance of concrete, at least in the lab (Bouzoubaâ et al. 2011, Hooton and Vassilev 2012). In the field though, concrete mixtures that incorporate SCMs have exhibited better scaling resistance than identical concrete mixtures tested in the laboratory in accordance with ASTM C672 (Bouzoubaâ et al. 2008). Concrete pavements with 50% slag cement replacement were observed after 15 years and did not show mass loss (Schlorholtz and Hooton 2008).

This study emphasizes the effect of using slag cement and Class C fly ash on the durability of concrete as affected both by the formation of calcium oxychloride and by scaling. Class C fly ash was chosen due to a lack of previous studies about scaling resistance of concrete incorporating

Class C fly ash. This chapter reviews previous studies and presents the objective and scope of this study.

1.2 PREVIOUS WORK

The following subsections review supplementary cementitious materials, mechanisms behind chemical reactions between deicing salts and concrete, and scaling of concrete. Several studies have emphasized the damage that can occur in concrete due to reactions between deicing salts and concrete through the use of wetting and drying tests. Other studies have focused on the scaling resistance of concrete containing SCMs. These studies are based on both laboratory tests and field investigations.

1.2.1 Supplementary Cementitious Materials (SCMs)

Mineral admixtures, such as slag cement and fly ash, are used as partial replacements of portland cement in many applications, including the construction of bridge decks. The use of either of these materials reduces greenhouse gas emissions, and the use of fly ash reduces the cost of producing concrete. The scaling resistance and durability of concrete containing either slag or fly ash at replacement percentages of cement ranging from 20% to 50% by volume are evaluated in this study. The following subsections provide details about these materials.

1.2.1.1 Fly Ash

Fly ash is a byproduct of the combustion of pulverized coal in power plants (ACI Committee 232.2R-18). In addition to the technical benefit of using fly ash as a partial replacement of portland cement, the cost of fly ash is about half the cost of portland cement. Fly ash and portland cement have the same mean particle diameter (between 10 and 15 µm), but using fly ash makes concrete more workable due to its spherical shape (Mindess et al. 2003). Due to the variety of chemical compositions in different fly ashes, ASTM C618 subdivides fly ash into two classes (C and F). Class C fly ash is a byproduct of the combustion of lignite coals, which are available in western states, mainly Wyoming and Montana, with a sum of the major acidic oxides (SiO_2 + Al_2O_3 + Fe_2O_3) greater than 50% but less than 70% of the material. Class F fly ash is a byproduct of the combustion of bituminous and subbituminous coals, which are available east of the Mississippi River, with a sum of the major acidic oxides greater than 70%.

1.2.1.2 Slag Cement

Slag cement is a byproduct of the production of pig iron, an intermediate product in the production of steel. Slag cement consists of ground calcium aluminosilicate glass, which is hydraulically active and formed due to rapid quenching of molten slag from a blast furnace. Slag cement, also called ground granulated blast-furnace slag, is rich in lime, silica, and alumina. The formation of impervious coatings around slag particles early in the hydration process slows the reaction between slag and water. Therefore, alkaline compounds, which can be either soluble salts or calcium hydroxide, are required to activate the slag. In practice, slags are activated by portland cement, which must represent 10% to 20% of the cementitious material, although the percentage is usually much higher (Mindess et al. 2003).

According to ASTM C989, slag cement is classified into three grades (80, 100, and 120) based on an activity index, defined as the ratio between the strength of mortars made with 50% slag and 50% portland cement and the strength of mortars made with 100% portland cement. The slag activity index is calculated at 7 and 28 days, as shown in Table 1.1

Table 1.1: Slag-Activity Index (ASTM C989)

Grade	Slag Activity Index, min percent			
	7 days		28 days	
	Average+	Individual*	Average+	Individual*
80	---	---	75	70
100	75	70	95	90
120	95	90	115	110

+Average of five consecutive samples
*Any individual sample

Replacing more than 25% of portland cement with slag cement may cause delays in the setting time, while using slag cement as a partial replacement for portland cement in mass concrete can reduce the heat of hydration (ACI Committee 233R-17).

1.2.2 Effect of Deicing Salts on Concrete

Deicing salts can cause concrete to deteriorate, especially at joints, as shown in Figure 1.1 (Jones et al. 2013). This damage can occur due to chemical changes within the cement paste and salt crystallization within the pores of both aggregate and cement paste.

Figure 1.1: Damage at joint (Jones et al. 2013)

Chemical changes occur when deicing salt solutions are transported into concrete, where chloride ions react with the aluminate and aluminoferrite phases forming Friedel's salt (Birnin-

Yauri and Glasser 1998, Qiao, Suraneni, and Weiss 2018a) and Kuzel's salt (Mesbah et al. 2011). In addition to the formation of Friedel's and Kuzel's salts, calcium chloride ($CaCl_2$) can react with calcium hydroxide $Ca(OH)_2$ and form calcium oxychloride ($CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$), as shown in Eq. (1.1) (Collepardi, Coppola, and Pistolesi 1994). Calcium oxychloride is expansive and causes deterioration in concrete (Farnam et al. 2015a, Qiao et al. 2017).

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \longrightarrow CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O \quad (1.1)$$

Magnesium chloride ($MgCl_2$) can also cause destructive chemical reactions in concrete. $MgCl_2$ causes a conversion of calcium silicate hydrate (C-S-H)[1], the principal hydration product in the cement paste, to noncementitious magnesium silicate hydrate (M-S-H) and $CaCl_2$, as shown in Eq. (1.2), causing a reduction in strength (Sutter et al. 2008 and Shi et al. 2011). In addition, magnesium chloride combines with $Ca(OH)_2$ to produce brucite (magnesium hydroxide) and additional $CaCl_2$, as shown in Eq. (1.3). Brucite combines with magnesium chloride to form magnesium oxychloride, as shown by Eq. (1.4) (Julio-Betancourt 2009). $CaCl_2$ combines with $Ca(OH)_2$ to produce calcium oxychloride, as shown in Eq. (1.1) (Sutter et al. 2006, and Farnam et al. 2015b).

$$\text{C-S-H} + MgCl_2 \longrightarrow \text{M-S-H} + CaCl_2 \quad (1.2)$$

$$Ca(OH)_2 + MgCl_2 \longrightarrow Mg(OH)_2 + CaCl_2 \quad (1.3)$$

$$(3 \text{ or } 5)Mg(OH)_2 + MgCl_2 + 8H_2O \longrightarrow (3 \text{ or } 5)Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O \quad (1.4)$$

Previous studies, which will be presented in the following section, have investigated the effects of deicing salts on concrete under cycles of wetting and drying (Sutter et al. 2006, Darwin

[1] C-S-H is cement chemists' notation for a range of hydration products that involve combinations of calcium oxide, silica, and water.

et al. 2008, Jain et al. 2012, Ghazy and Bassuoni 2017). These studies investigated different salt concentrations and exposure conditions. To evaluate the physical changes in concrete, visual inspection was performed and changes in the relative dynamic modulus were studied, coupled with petrographic analysis, observation with a scanning electron microscope (SEM), and x-ray microanalysis.

Suraneni et al. (2016) studied the formation of calcium hydroxide experimentally using thermogravimetric analysis (TGA) and theoretically using thermodynamic models developed using GEMS software (Kulik et al. 2013). These models estimate the quantity of calcium hydroxide based on the degree of hydration of cement and the degree of reaction of SCMs. The formation of calcium oxychloride was also investigated using low-temperature differential scanning calorimetry (LT-DSC). Cement pastes with water-cementitious material (*w/cm*) ratios of 0.36 and 0.50 and incorporating slag cement and Class F fly ash at replacement levels of 0%, 20%, 40%, and 60% by *volume* of cement were used. Cement pastes were cast in 1.5 × 2 in. (38 × 50 mm) cylindrical molds, and cured under sealed conditions at 73 ± 3 ºF (23 ± 1 ºC) for 3, 7, 28, and 49 days; in addition, some specimens were cured under sealed conditions at room temperature for 3 days, followed by 25 days of curing under sealed conditions at 122 ºF (50 ºC). At the end of the curing period, the cylinders were ground down, and the resulting powder was passed through a 75 µm sieve. The material that passed through the sieve was then studied using the TGA test, which evaluated the amount of calcium hydroxide and the LT-DSC test, which evaluated the amount of calcium oxychloride.

Upon the completion of the tests, it was observed that the amount of calcium oxychloride increased linearly with the amount of calcium hydroxide. Increasing the *w/cm* ratios increased the calcium hydroxide formation, leading to an increase in the formation of calcium oxychloride. For the cement pastes with 100% cement, the amounts of calcium hydroxide and calcium oxychloride increased as the age of the samples increased. For the cement pastes with different percentage replacements of cement with SCMs, the amounts of calcium hydroxide and calcium oxychloride also increased for specimens with age up to 7 days. At ages greater than 7 days, however, the amounts of calcium hydroxide and calcium oxychloride decreased for specimens containing SCMs. This presumably occurred as a result of the pozzolanic reaction and dilution caused by use of the SCMs.

Qiao et al. (2017) conducted an experimental study to construct a phase diagram for calcium oxychloride as a function of concentration and temperature using low-temperature differential scanning calorimetry (LT-DSC) and measure the volume change caused by the formation of calcium oxychloride. To construct the phase diagram, $Ca(OH)_2$ powder was added to a $CaCl_2$ solution with different concentrations (5%, 10%, 15%, 20%, 25%, and 30% by weight) to achieve a molar ratio of $Ca(OH)_2/CaCl_2$ of 1.0. Figure 1.2 shows the phase diagram of the calcium oxychloride. This phase diagram reveals that the formation of calcium oxychloride is a function of both the temperature and the concentration of the $CaCl_2$ solution. For example, if the concentration of $CaCl_2$ solution is 5% and the temperature is 68 ºF (20 ºC), calcium oxychloride does not form; while for the concentration of $CaCl_2$ solution is 20%, the calcium oxychloride will be formed at any temperature below 86 ºF (30 ºC). A key point in the process is that not only will calcium oxychloride form at lower temperatures but that the chemical species change with increases and decreases in temperature, which will lead to deterioration of the paste constituent of concrete.

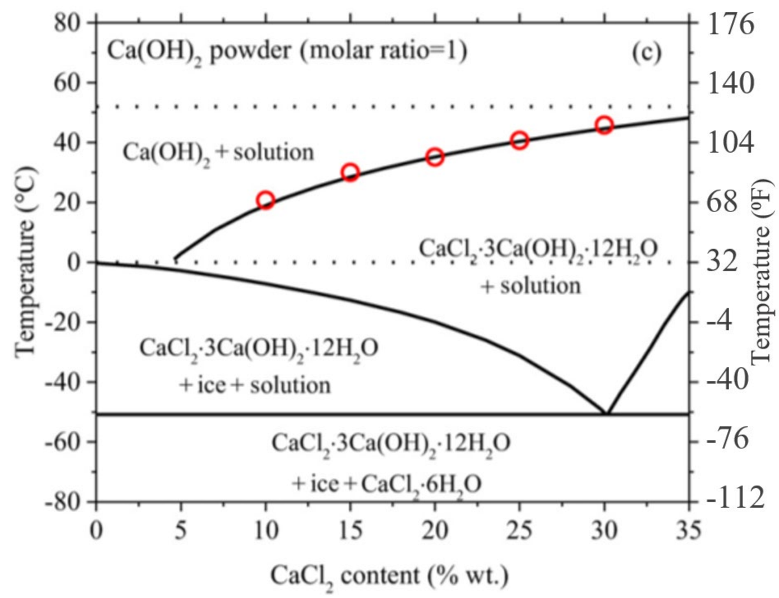

Figure 1.2: Phase isopleth of ($Ca(OH)_2$ - $CaCl_2$ - H_2O) ternary system (Qiao et al., 2017) - *modified*

1.2.3 Evaluating the Effect of Deicing Salts on Concrete by Using Wetting and Drying Tests

Darwin et al. (2008) investigated changes in the properties of concrete that were exposed to sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), or calcium magnesium acetate (CMA) with molal ion concentrations of 6.04 and 1.06. Specimens exposed to air and distilled water served as controls. Portland cement was the only cementitious material used, the water-cement (*w/c*) ratio was 0.45, and the exposing 3 × 3 × 12 in. (76 × 76 × 305 mm) prismatic specimens were demolded after 24 hours, cured for 6 days in lime-saturated water, then dried for 48 days at 73 ± 3 ºF (23 ± 1.7 ºC) and a relative humidity (RH) of 50% ± 4%. The test procedure consisted of exposing the test specimens to one of the solutions for 4 days at 73 ± 4 ºF (23 ± 2 ºC), then exposing them to 3 days of drying at 100 ± 3 ºF (38 ± 1.7 ºC). Cycles were continued up to 95 weeks; every 5 weeks the distilled water and saline solutions were changed, and the dynamic modulus of elasticity based on the fundamental transverse resonance frequency was recorded. A visual evaluation at the end of the test was also used to assess the physical damage of concrete specimens.

The high and low concentration solutions for the NaCl and the low concentration solution for the $CaCl_2$ did not negatively impact the specimens. However, the high concentration solutions of the $CaCl_2$, $MgCl_2$, and CMA caused significant damage to the concrete. The low concentration solutions of both $MgCl_2$ and CMA also caused noticeable, but lesser, damage.

Jain et al. (2012) investigated the effects of exposure to sodium chloride (NaCl), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$) on the physical and mechanical properties of a control mixture without an SCM and a mixture with a 20% replacement of cement with Class C fly ash at a *w*/*cm* ratio of 0.42. The study examined the effects of wetting-drying and freezing-thawing. Saline solutions with molal ion concentrations of 10.5 and 5.5 were used, respectively, for the wetting-drying and freezing-thawing tests.

Three 3 × 3 × 11.5 in. (76 × 76 × 292 mm) prismatic test specimens and two 4 × 8 in. (100 × 200 mm) cylinders were used for the wetting-drying test. The concrete specimens were cured for 28 days at 73.4 ºF (23 ºC) and 100% (RH) and dried for three days at 73.4 ºF (23 ºC) and 50% RH before starting the exposure cycles. The exposure conditions for the wetting-drying test included submerging specimens in solutions for 16 ± 1 hour at 39.2 ºF (4 ºC) and drying them for 8 ± 1 hour at 73.4 ºF (23 ºC) and 50% RH. For the freezing-thawing test, the exposure conditions incorporated cooling specimens from 71.6 ºF (22 ºC) to -4 ºF (-20 ºC) over 9 hours, keeping them at -4 ºF (-20 ºC) for 5 hours, and warming them from -4 ºF (-20 ºC) to room temperature at 71.6 ºF (22 ºC) over 6 hours.

Visual evaluation, ultrasonic pulse velocity (UPV), compressive strength, mass change, dynamic modulus of elasticity, and rate of chloride ion penetration were used to assess the properties of concrete specimens after exposure to deicing salts. Calcium chloride ($CaCl_2$) was the most harmful salt for the control concrete specimens. The reductions in the relative values of UPV reveal that magnesium chloride ($MgCl_2$) required more time than $CaCl_2$ to cause microstructural cracking for the control concrete specimens. Sodium chloride (NaCl) did not have a negative impact on the concrete. In addition to the previous conclusions, the use of fly ash resulted in a noticeable improvement in the relative dynamic modulus of the concrete specimens that were exposed to both wetting-drying and freezing-thawing exposure cycles.

Ghazy and Bassuoni (2017) examined the damage to concrete caused by exposure to different deicing salt solutions (NaCl, $CaCl_2$, $MgCl_2$, and $CaCl_2$+$MgCl_2$) with a chloride molar concentration of 4.5. The study involved a control concrete mixture with 100% cement and mixtures containing 6% nanosilica, 20% Class F fly ash, 30% Class F fly ash, 20% Class F fly ash and 6% Nano silica, 30% Class F fly ash and 6% nanosilica replacements of cement by mass. The nanosilica, which was in a colloidal form, had a mean particle size of 0.035 µm and a specific gravity of 1.4. The mixtures had a *w/cm* ratio of 0.4. Specimens were cured for 28 days at 72 ± 3 ºF (22 ± 2 ºC) and 98% relative humidity. Two exposure procedures were used: (1) submerging the specimens in deicing salt solutions at a temperature of 41 ºF (5 ºC) for 540 days and (2) submerging specimens in the deicing solutions at 41 ºF (5 ºC) for two days, drying specimens at 73 ± 3 ºF (23 ± 2 ºC) and a relative humidity of 55 ± 5 % for two days, and then drying specimens at 104 ± 3 ºF (40 ± 2 ºC) and relative humidity of 30 ± 5 % for one day; the cycles of wetting and drying were continued for 504 days. The dynamic modulus of elasticity, rapid chloride penetration test, mass change, expansion, and visual evaluation were used to assess the concrete specimens.

Exposure to a NaCl solution had little effect on the concrete specimens for either exposure condition. For specimens that incorporated 100% cement and were exposed to $CaCl_2$, damage was faster under wetting and drying than for immersion. X-ray diffraction (XRD) showed that at the end of the wetting period, calcium oxychloride, Friedel's salt, and ettringite were formed; while at the end of drying period, the calcium oxychloride was converted to ($CaCl_2 \cdot Ca(OH)_2 \cdot 2H_2O$) or ($CaCl_2 \cdot Ca(OH)_2$). Therefore, the combined effects of salt crystallization and reversible formation of different forms of calcium oxychloride were the reasons behind the faster damage of wetting and drying procedure than the immersion procedure. In addition, significant damage occurred to the concrete specimens exposed to the combined $CaCl_2$ and $MgCl_2$ solutions. Using supplementary cementitious materials improved the physical and chemical resistance of concrete specimens.

1.2.4 Scaling of Concrete

Scaling is defined as damage to the surface layer of concrete, which causes spalling of small pieces of mortar and surface aggregates, as shown in Figure 1.3. There are several mechanisms that may contribute to scaling of concrete. The lower vapor pressure of salt solutions compared with pure water reduces the rate of evaporation and, thus, increases the degree of saturation of concrete. The use of deicing salt to melt ice on the surface of concrete can cause a rapid drop in the temperature of concrete below the surface layer. Damage in the concrete can occur due to subsequent rapid freezing or from tensile stresses from the thermal strains. In both mechanisms, microscopic or macroscopic ice lenses are formed due to the free moisture near the surface of the concrete. In addition to the vapor pressure and rapid freezing, adding deicing salt on the surface of concrete causes a difference in the concentration of pore solution and increases the effects of osmotic pressure (Mindess et al. 2003).

Figure 1.3: Scaling of concrete (Lindquist et al. 2008)

Valenza (2005) proposed an alternate mechanism for scaling described as glue spalling. Glue spalling is a technique used in decorative works and causes the formation of shallow scallops in glass. The glue spall theory is based on a change in temperature and occurs when bonded materials have differing thermal coefficients. This mechanism involves blasting the surface of the glass to roughen it and then applying epoxy to it at a high temperature. Reducing the temperature causes the epoxy layer to fracture into small pieces as it contracts. This contraction will develop tensile stress in the glass; cracks will occur once the tensile stress reaches the tensile strength of the glass. According to Valenza (2005), the glue spall mechanism explains scaling of concrete, where the ice acts in a manner similar to the epoxy, and the concrete acts as glass. Due to the difference in the thermal expansion coefficients (the thermal expansion coefficient of ice is approximately five times the coefficient of concrete), cracks will develop.

Verbeck and Klieger (1957) observed that the scaling resistance of concrete is affected by the concentration of salt in the saline solution, with the greatest amount of damage occurring at salt concentrations between 2% and 4% for both sodium chloride and calcium chloride. During casting of concrete, overvibrating and overfinishing the concrete reduce the scaling resistance of concrete due to increasing cement paste (cement and water) and reducing air voids on the surface (Mindess et al. 2003). ASTM C672 and Quebec standard BNQ NQ 2621-900 are the most common tests used in the US and Canada to assess the scaling resistance of concrete.

1.2.5 Scaling Resistance of Concrete Containing SCMs

Bilodeau et al. (1998) conducted a study investigating the scaling resistance of seven concrete mixtures. These mixtures involved percentage replacements of cement with Class F fly ash of 0%, 25%, 35%, and 58% by mass of portland cement and *w/cm* ratios ranging from 0.32 to 0.45. The study also included two curing regimes (moist curing and curing compounds), different curing and drying periods, and the surface condition compared the behavior of concrete with a finished surface (cast horizontally) versus concrete with a formed surface (cast vertically). The scaling tests were performed in accordance with ASTM C672 using a 3% sodium chloride solution.

The results showed that concrete mixtures containing fly ash scaled more than the control mixtures. Concrete mixtures with up to 35% fly ash by mass of cementitious materials with a *w/cm* ratio of 0.4 or lower had an acceptable scaling resistance (the mass loss was below the limit of 0.16 lb/ft^2); these concrete mixtures were cured for 14 days and dried for 14 days prior to being tested. Extending moist curing periods beyond 14 days slightly improved the scaling resistance of the concrete mixture with 58% fly ash. However, in other mixtures (25% and 35% fly ash with a *w/cm* ratio of 0.4), extending the curing period caused a significant reduction in scaling resistance. The scaling resistance of concrete specimens improved greatly when curing compounds were used.

Schlorholtz and Hooton (2008) investigated the scaling resistance of concrete mixtures incorporating SCMs as 25% to 50% weight replacements of portland cement in bridge decks and pavements with ages ranging from 3 to 17 years. In addition to the visual inspections, 6-inch diameter cores were extracted from six pavements and six bridge decks. The core samples were tested for scaling in accordance with ASTM C672, rapid chloride permeability, and surface chloride profiles, and subjected to petrographic examination. The field investigations showed that some pavements and bridge decks with concrete mixtures incorporating different percentage replacements of cement with SCMs exhibited some scaling or other surface damage while others did not. The main conclusions from this study were that construction procedures had a greater effect on the scaling resistance of concrete than the percentage replacements of cement with SCMs. For example, for some sites that exhibited scaling, petrographic examination showed that extra water had been added to the concrete after initial batching, while others had values of the *w/cm* ratio that were noticeably higher than the original design value.

Based on the recommendations by Schlorholtz and Hooton (2008), Hooton and Vassilev (2012) investigated the scaling resistance of concrete mixtures with different slag types and contents. Three scaling test procedures were used: ASTM C672 with 4% $CaCl_2$ and a modified BNQ 2621-900 with 3% NaCl for two curing regimes. The modification to the BNQ 2621-900 incorporated using 50 cycles of freezing and thawing instead of 56 cycles and also evaluating the mass loss after 5, 10, 15, 25, and 50 cycles. The curing regimes included normal curing (14 days in a moist room at 77 ºF (25 ºC)) and accelerated curing (7 days in a moist room at 77 ºF (25 ºC) and 21 days in a moist room at 100 ºF (38 ºC); during these the 21 days, specimens were submerged in a 4g/L $Ca(OH)_2$ solution). This curing regime was based on the accelerated curing procedure of Virginia Department of Transportation (Ozyildirim 1998). The specimens tested in accordance with ASTM C672, were cured for 14 days in a moist room at 77 ºF (25 ºC), followed by 14 days of drying at 50% RH. The specimens tested in accordance with the modified BNQ 2621-900 with the normal curing, were exposed to 14 days of drying at 50% RH; while most of the specimens were cured using the accelerated curing regime that did not include a drying period, except specimens of one mixture that was exposed to 14 days of drying at 50% RH. The specimens, that were tested in accordance with the modified BNQ 2621-900 procedure were had re-saturation periods, which included ponding NaCl solution on the surface of the specimen for 7 days before exposure to freeze-thaw cycles. The study evaluated 16 concrete mixtures with both low and high alkali cements. Grade 100 and 120 slag cements were used with 0%, 20%, 35%, and 50% replacement by mass of portland cement.

The test results showed that there was no direct relationship between compressive strength and scaling resistance and that scaling resistance decreased as the percentage replacement of cement with the slag cement increased. Reducing the *w/cm* ratio from 0.42 to 0.38 improved the scaling resistance. Specimens with 100% cement showed more mass loss when tested in accordance with ASTM C672 than when tested with the modified BNQ 2621-900 with normal curing. Specimens with high slag cement contents, however, showed less mass loss when tested in accordance with ASTM C672 than when tested using the modified BNQ 2621-900 with both normal and accelerated curing regimes. For specimens with 20% and 35% of slag cement, it was not clear which test procedure resulted in more mass loss. The majority of the scaling occurred in the first 15 cycles when testing in accordance with ASTM C672, whereas low amounts of scaling occurred during the first 15 cycles when testing using the modified BNQ 2621-900 procedure with both normal and accelerated curing. The finishing procedure (brushing) used in ASTM C672, which caused trapping of bleed water in the upper surface layer of concrete may have caused damage in the air void system and might be the reason behind the majority of mass loss during the first 15 cycles when testing in accordance with ASTM C672. The differences in behavior, however, are likelit also a function of the different deicing chemicals used in the two test procedures, a 4% $CaCl_2$ solution with ASTM C672 and a 3% NaCl solution for the modified BNQ 2621-900 procedure. The authors recommended extending the curing period to 28 days, especially for concrete with SCMs.

Bouzoubaâ et al. (2008) published Phase I of a study that compared the scaling resistance for seven concrete mixtures based on laboratory tests (ASTM C672 and BNQ 2621-900) and field environment exposure after four winters. The study investigated the effects of silica fume, Class F fly ash, and Grade 100 slag cement and concrete maturity on scaling resistance. The study included five binary blended mixtures with replacements by weight of cement of 2% silica fume, 25% fly ash, 35% fly ash, 25% slag cement, and 35% slag cement, and two ternary blended mixtures with replacements by weight of cement of 20% fly ash/5% silica fume and 20% slag cement/5% silica fume.

In the field, a sidewalk was divided into seven subsections with dimensions of 110 × 146 in. (2800 × 3700 mm). For each concrete mixture, one sidewalk subsection, one slab with a dimension of 47 × 47 in. (1200 × 1200 mm), and two laboratory slabs, which were tested in accordance with ASTM C672, with a dimension of (300 mm × 300 mm × 75 mm) were cast for each concrete mixture. In addition, 14 laboratory slabs, which were tested in accordance with BNQ 2621-900, were cast for each of the concrete mixtures.

The sidewalk subsections, slabs, and laboratory slabs were cast in the field in May 2002 and cured by using wet burlap and covered with plastic sheets for two days. After two days, the laboratory slabs were moved to a moist curing room at 73 ºF (23 ºC) for 12 days. Cores were extracted from the slabs at an age of two days and transported to the laboratory for 12 days of curing in a moist room at 73 ºF (23 ºC). These cores were tested in accordance with ASTM C672. At the end of curing period, all laboratory slabs and cores were exposed to 14 days of drying. At the end of the drying period, the BNQ 2621-900 procedure requires a seven-day re-saturation period, which includes ponding with a NaCl solution. At an age of 180 days, additional cores were extracted from the slabs and moved to the laboratory for the scaling test in accordance with ASTM C672. These cores were exposed to the freezing-thawing cycles without curing or drying. A 3% NaCl solution, was used to evaluate the scaling resistance of the mixtures for both ASTM C672 and BNQ 2621-900 tests.

The mass loss of concrete mixtures containing fly ash showed that testing following ASTM C672 resulted in more mass loss than obtained with BNQ 2621-900. The concrete mixtures containing slag cement exhibited better scaling resistance in laboratory tests than the mixtures that incorporated fly ash. Field evaluations after four winters found that the concrete that incorporated 2% silica fume and the two slag concretes showed good scaling resistance, the fly ash concrete showed acceptable scaling resistance, and the ternary blended mixtures showed poor scaling resistance. A comparison between the laboratory scaling tests (ASTM C672 and BNQ) and scaling of concrete in the field after four winters indicated that ASTM C672 was excessively severe and the BNQ method was adequate for evaluating the scaling resistance of the concrete mixtures that incorporated SCMs.

Bouzoubaâ et al. (2011) published Phase II of the study, which included three concrete mixtures with replacements of cement by 2% silica fume or 25% Class F fly ash, and a ternary mixture with a 20% Class F fly ash and 5% silica fume replacement of cement by mass. The purpose of this phase was to compare the scaling resistance of the concrete mixtures in the laboratory with that of three of the sidewalks cast in October 2002 to study the performance of the concretes under field conditions. The study also investigated the effect of casting date on the scaling resistance of concrete.

In the field, the sidewalk was divided into six subsections with dimensions of 59 × 146 in. (1500 × 3700 mm). For each concrete mixture, two sidewalk subsections, two slabs with a dimension of 35 × 47 in. (900 × 1200 mm), and 10 laboratory slabs, which were tested in accordance with ASTM C672 and BNQ 2621-900, were cast for each concrete mixture. Also, 12 laboratory slabs, which were tested in accordance with BNQ 2621-900, were cast for each concrete mixture.

The sidewalk subsections, slabs, and laboratory slabs were cast in the field in October 2002. For the sidewalk subsections and slabs, two curing procedures were used: wet burlap covered with plastic sheets for two days or curing compound. For the laboratory slabs three curing procedures were used: wet burlap covered with plastic sheets for two days in the field followed by 12 days of curing in the moist room at 73 ºF (23 ºC), 14 days of curing in the moist room at 73 ºF (23 ºC), or curing compound. Cores were extracted from the slabs at an age of two days and cured in the laboratory for 12 days in a moist room at 73 ºF (23 ºC). These cores were tested in accordance with ASTM C672. All laboratory slabs and cores were exposed to 14 days of drying once the curing period has been completed. Some of the laboratory slabs, which were tested in accordance with ASTM C672 or BNQ 2621-900, were exposed to 7 days of re-saturation with NaCl solution on the surface of the specimen before the beginning of the freezing-thawing cycles.

In addition, other cores were extracted from the slabs at an age of 28 days and moved to the laboratory. These cores were tested in accordance with ASTM C672, and the test was started once the cores arrived the laboratory without curing or drying. The ASTM C672 and BNQ 2621-900 tests, both with a 3% NaCl solution, were used to evaluate the scaling resistance of the mixtures.

Based on the laboratory tests and field investigations after six winters, the concrete containing fly ash showed lower scaling resistance than the mixture that incorporated 2% silica fume, in both the laboratory scaling tests and field visual evaluations. The concrete mixture with fly ash had better scaling resistance when tested in accordance with BNQ 2621-900 than when tested in accordance with ASTM C672. Both laboratory tests and visual field evaluations indicated that the use of curing compound improved scaling resistance. Comparing the scaling resistance of the cores obtained from the slabs to that of the specimens that were finished in accordance with ASTM C672 showed that the finishing procedure for ASTM C672 fairly represents field finishing. Due to maturity and drying, the field evaluation revealed that concrete mixtures cast in October 2002 scaled more than the same concrete mixtures cast in May 2002, as described earlier Bouzoubaâ et al. (2008).

Houehanou, Gagné, and Jolin 2010 cast five concrete mixtures to study the scaling resistance of concrete incorporating SCMs. The mixtures, with cement replacements of 2% silica fume, 35% Class F fly ash, 25% Class F fly ash and 1% silica fume, 35% slag cement, and 25% slag cement and 1% silica fume, were similar to the mixtures evaluated by Bouzoubaâ et al. (2008). In this study, the scaling resistance of concrete mixtures was compared following the procedures in ASTM C672 and BNQ 2621-900 using a 3% NaCl solution; the effects of curing periods, pre-saturation periods, and the presence of a geotextile layer at the bottom of the specimen on the scaling resistance were also evaluated. Moist curing periods of 14, 28 and 91 days were used for ASTM C672 while curing periods of 14 and 28 days were used for BNQ 2621-900. Two re-saturation periods, which included ponding NaCl solution on the surface of the specimen for a specific time (7 and 28 days) before exposing to freeze-thaw cycles, were used for the scaling tests for the BNQ 2621-900 tests.

The curing period had a noticeable effect on the scaling resistance; 28 days of moist curing improved the scaling resistance for all concrete mixtures, particularly the mixtures that incorporated fly ash. Increasing the moist curing beyond 28 days did not result in much additional improvement in the scaling resistance. The mass loss of the specimens tested in accordance with ASTM C672 was greater than that evaluated under BNQ 2621-900, with the reason being the re-saturation period used in the BNQ test, which has been shown to result in less scaling than in tests without re-saturation (Houehanou et al. 2010). Neither increasing the re-saturation period to 28 days nor using geotextile layers at the bottom of the specimens had a significant effect on scaling resistance.

Sobolev et al. (2017) evaluated the performance of concrete mixtures incorporating Class F and C fly ash. The experimental program included 10 mixtures: 100% cement, 15% Class F FA, 30% Class F FA, 30% Class C FA, and a combination of 15% Class C FA and 15% Class F FA; these five combinations were evaluated in conjunction with both mid-range and high-range water reducing admixtures. Freeze-thaw tests following ASTM C666 Procedure A and scaling resistance tests according to ASTM C672 were used to investigate the durability performance of the concrete mixtures. Specimens for both the freeze-thaw and scaling tests were cured for 28 days in a moist room. In the scaling test procedure, each freeze-thaw cycle takes 48 hours, 24 hours for freezing and 24 hours for thawing.

The results indicate that Class C fly ash provided better scaling resistance than Class F fly ash. Mixtures with 30% Class C fly ash showed mass loss comparable to that for control mixtures, which incorporated 100% cement. Among all mixtures, concrete mixtures with 30% Class F fly ash and a combination of 15% Class C FA and 15% Class F FA exhibited greater scaling resistance than the other mixtures in the study. All mixtures showed excellent freeze-thaw resistance when tested in accordance with ASTM C666.

1.3 OBJECTIVE AND SCOPE

Supplementary cementitious materials (SCMs) are commonly used as partial replacements of portland cement in the construction of bridge decks and pavements. The use of SCMs in concrete mixtures appears to have different effects on the durability of concrete depending on the nature of the test and the type of exposure. Using SCMs has a negative effect on the scaling resistance of concrete, especially for concrete specimens tested in the laboratory. In these cases, scaling resistance decreases with increases in the percentage of cement replacement with SCMs. Other studies, however, have shown that using SCMs, even with high percentage replacements, enhances the durability of concrete primarily by reducing the formation of calcium oxychloride. Part of the difference in performance appears to be a function of the deicing chemical involved. In prior studies, no attempts were made to investigate both scaling resistance and damage to concrete due to exposure to deicing salts through wetting and drying cycles on the same concrete mixtures. There is a clear need to establish a reasonable range for the replacement percentage of portland cement with SCMs that can achieve a balance in performance against both scaling and damage due to exposure to deicing salts.

In this study, Class C fly ash was selected because there is a lack of prior work studying the scaling resistance of concrete mixtures that include Class C fly ash. In this study, mixtures with two *w/cm* ratios, 0.38 or 0.44, are studied. Mixtures with a *w/cm* ratio 0.44 are often used in the field, whereas mixtures with a *w/cm* ratio of 0.38 are used less often because they usually entail the use of more cementitious material and, thus, higher cost in cases where the accompanying higher compressive strength is not needed.

The objective of this study is to investigate the durability of concrete containing slag cement and Class C fly ash and find cement replacement percentages of these SCMs that provide good overall performance for concrete subjected to different deicing chemicals under freezing conditions. The study includes 14 mixtures involving tests of 204 specimens to investigate the effects of deicing salt type (sodium chloride, calcium chloride, or magnesium chloride), water-to-cementitious material ratio (0.38 and 0.44), and percentage replacement of cement with SCMs (20%, 35%, and 50% by volume of cement) when subjected to wetting and drying to evaluate damage due to the formation of calcium oxychloride. Exposure conditions consist of submerging concrete specimens in solutions for 17 ± 1 hour at 39.2 ºF (4 ºC) followed by drying for 7 ± 1 hour at 73 ± 3 ºF (23 ± 2 ºC) and 50% ±4% RH. The study also includes 10 mixtures (156 specimens) to study the effects of curing period, deicing salt type (sodium chloride or calcium chloride), water-to-cementitious material ratio (0.38 and 0.44), and percentage replacement of cement with SCMs (20%, 35%, and 50% by volume of cement) on the scaling resistance of concrete tested in accordance with the Quebec test BNQ NQ 2621-900. The test results are used to provide recommendations on the selection of cementitious materials and the design of concrete mixtures that may be subjected to a range of deicing chemicals in the field.

CHAPTER 2 - EFFECTS OF DEICING SALTS ON CONCRETE INCORPORATING SLAG CEMENT OR CLASS C FLY ASH

2.1 INTRODUCTION

During winter, it is common to use deicing salts, such as sodium chloride (NaCl), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$), to melt ice. Using these salts, however, can cause deterioration of concrete. This deterioration may occur due to the effects of salt crystallization inside the pores of aggregates and cement paste. Chemical reactions between the deicing salts and concrete can also occur when deicing salt solutions penetrate concrete, where they react with aluminate and aluminoferrite phases forming Friedel's salt (Birnin-Yauri and Glasser 1998, Qiao, Suraneni, and Weiss 2018a) and Kuzel's salt (Mesbah et al. 2011). Furthermore, calcium chloride ($CaCl_2$) can react with calcium hydroxide ($Ca(OH)_2$), which is produced during the hydration of portland cement, and from calcium oxychloride ($CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$), as shown in Eq. (2.1) (Collepardi, Coppola, and Pistolesi 1994).

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \longrightarrow CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O \quad (2.1)$$

When formed, calcium oxychloride occupies a greater volume than its constituents, thus causing internal tensile stresses and deterioration of concrete. This deterioration occurs most often at joints and cracks (Farnam et al. 2015a, Farnam et al. 2015b, Qiao, Suraneni, and Weiss 2017).

Magnesium chloride ($MgCl_2$) can also cause destructive chemical reactions in concrete. $MgCl_2$ causes a conversion of calcium silicate hydrate (C-S-H)[2], the principal hydration product in the cement paste, to noncementitious magnesium silicate hydrate (M-S-H) and $CaCl_2$, as shown in Eq. (2.2), causing a reduction in strength (Sutter et al. 2008 and Shi et al. 2011). In addition,

[2] C-S-H is cement chemists' notation for a range of hydration products that involve combinations of calcium oxide, silica, and water.

magnesium chloride combines with $Ca(OH)_2$ to produce brucite (magnesium hydroxide) and additional $CaCl_2$, as shown in Eq. (2.3). Brucite combines with magnesium chloride to form magnesium oxychloride, as shown by Eq. (2.4) (Julio-Betancourt 2009). $CaCl_2$ combines with $Ca(OH)_2$ to produce calcium oxychloride, as shown in Eq. (2.1) (Sutter et al. 2006, and Farnam et al. 2015b).

$$\text{C-S-H} + MgCl_2 \longrightarrow \text{M-S-H} + CaCl_2 \tag{2.2}$$

$$Ca(OH)_2 + MgCl_2 \longrightarrow Mg(OH)_2 + CaCl_2 \tag{2.3}$$

$$(3 \text{ or } 5)Mg(OH)_2 + MgCl_2 + 8H_2O \longrightarrow (3 \text{ or } 5)Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O \tag{2.4}$$

Figure 2.1, a phase diagram of calcium oxychloride constructed by Qiao et al. (2017), shows that the formation of calcium oxychloride is dependent on the temperature and the concentration of the $CaCl_2$ solution. For example, if the concentration of the $CaCl_2$ solution is 5% and the temperature is 68 ºF (20 ºC), calcium oxychloride does not form; while for a concentration of $CaCl_2$ solution 20%, calcium oxychloride will be formed at any temperature below 86 ºF (30 ºC).

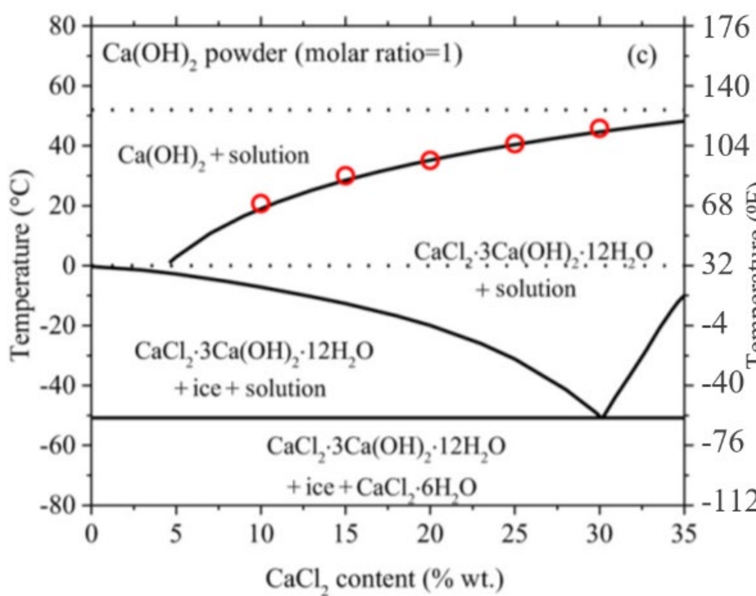

Figure 2.1: Phase isopleth of the $Ca(OH)_2$ - $CaCl_2$ - H_2O ternary system (Qiao et al. 2017) - *modified*

Wetting and drying tests have been used to study the effects of deicing salts on concrete. In these tests, concrete is subjected to cycles of wetting and drying while exposed to deicing salts (Sutter et al. 2006, Darwin et al. 2008, Jain et al. 2012, Ghazy and Bassuoni 2017). The effects of the deicing chemicals can be evaluated based on visual inspection, changes in the relative dynamic modulus of elasticity, and by utilizing petrographic analysis, scanning electron microscope (SEM), and X-ray microanalysis.

Ghazy and Bassuoni (2017) found that calcium oxychloride forms in concrete when specimens were submerged for two days in $CaCl_2$ solution with a concentration of 21.9% and temperature of 41 ºF (5 ºC), as predicted by the phase diagram in Figure 2.1. Because calcium oxychloride is expansive, concrete is damaged. Upon drying for two days at 73 ± 3 ºF (23 ± 2 ºC) and a relative humidity of 55 ± 5 %, followed by one additional day of drying at 104 ± 3 ºF (40 ± 2 ºC) and a relative humidity of 30 ± 5 % Ghazy and Bassuoni (2017) observed that this hydrous form of calcium oxychloride ($CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$) is converted to one of two anhydrous forms $CaCl_2 \cdot Ca(OH)_2 \cdot 2H_2O$ or $CaCl_2 \cdot Ca(OH)_2$. Re-submerging specimens in $CaCl_2$ solution converts these anhydrous forms of calcium oxychloride back into the hydrous form, and vice-versa upon drying. This reversible formation of hydrous and anhydrous forms of calcium oxychloride causes greater damage to concrete exposed to cycles of wetting and drying than keeping concrete submerged in $CaCl_2$ solution and not exposed to drying.

Among deicing salts, $CaCl_2$ and $MgCl_2$ are considered the most harmful to concrete, with $CaCl_2$ causing the greatest amount of deterioration (Jain et al. 2012). The cause of this deterioration has been attributed to the formation of calcium oxychloride, as described above. Unlike $CaCl_2$ and $MgCl_2$, NaCl does not result in the formation of calcium oxychloride and, thus, causes less damaging.

The use of supplementary cementitious materials (SCMs) as a partial replacement of portland cement can reduce the formation of calcium oxychloride (Jain et al. 2012, Suraneni et al. 2016, Ghazy and Bassuoni 2017) because they reduce the quantity of calcium hydroxide available to react with calcium chloride. Using SCMs, however, can have a negative impact on the scaling resistance of concrete, as will be discussed in Chapter 3. Therefore, there is an essential need to study how much cement can be replaced with SCMs to minimize damage due to the formation of calcium oxychloride while also minimizing scaling.

In the current study, the effects of deicing salt type, replacement percentage of SCMs, and water-cementitious material (*w/cm*) ratio on the damage of concrete are evaluated. Previous investigations have not addressed the effect of different replacement percentages of SCMs or *w/cm* ratio on the durability of concrete exposed to deicing salts under wetting and drying.

2.2 RESEARCH SIGNIFICANCE

Although prior studies have shown that using SCMs can reduce the formation of both calcium hydroxide and calcium oxychloride, a number of issues still need to be addressed, as explained earlier. This study emphasizes the effects of deicing salt type (NaCl, $CaCl_2$, or $MgCl_2$), replacement percentage of SCMs (20%, 35%, or 50% of slag cement or Class C fly ash), and *w/cm* ratio (0.38 or 0.44) on the damage of concrete exposed to deicing salts.

2.3 EXPERIMENTAL WORK

2.3.1 Materials

Type I/II portland cement was used in all concrete mixtures. The SCMs, Class C fly ash and Grade 100 slag cement, were used as volume-based partial replacements of portland cement. The water-to-cementitious material ratio (*w/cm*) was, as usual, based on weight (mass), while the paste content was kept constant at 25% based on assumed air content of 8% to avoid increasing the paste volume when SCMs were used. Table 2.1 summarizes the chemical compositions of the cementitious materials.

Table 2.1: Chemical composition (percentage) and specific gravity of cementitious materials

Component	Portland cement	Class C fly ash	Grade 100 slag cement
SiO_2	20.82	34.99	34.92
Al_2O_3	4.18	17.06	7.64
Fe_2O_3	3.11	5.33	0.69
CaO	62.84	30.41	40.94
MgO	2.08	4.54	10.25
SO_3	2.56	1.87	2.72
Na_2O	0.22	1.47	0.3
K_2O	0.56	0.55	0.55
TiO_2	0.25	1.33	0.37
P_2O_5	0.08	0.79	0.01
Mn_2O_3	0.10	0.04	0.53
SrO	0.24	0.31	0.05
Cl^-	0.01	-	0.05
BaO	-	0.35	0.02
LOI	2.96	0.65	0.97
Total	99.99	99.68	100.01
Specific Gravity	3.14	2.63	2.89

Granite was used as the coarse aggregate, separated in size fractions (A and B) with maximum sizes of ¾ and ½ in. (19 and 13 mm), respectively, to help optimize the gradation. Size fraction A had an absorption of 0.71% and specific gravity (saturated-surface dry, SSD) of 2.61; size fraction B granite had an absorption of 0.87% and specific gravity (SSD) of 2.60. Pea-gravel and Kansas River sand were used as the fine aggregates. The absorptions of pea-gravel and Kansas River sand were 1.3% and 0.42%, respectively, and the specific gravities (SSD) were 2.60 and 2.61, respectively. An air-entraining admixture (AEA, Euclid AEA-92S) and a high-range water reducer (HRWR, Euclid Plastol 6400) were also used.

2.3.2 Concrete Mixtures

Fourteen concrete mixtures (204 specimens) were cast to study the effects of deicing salt type, water-to-cementitious material ratio (*w/cm*), and replacement percentage of SCMs on the damage of concrete due to wetting and drying in the presence of deicing salts. Test specimens were exposed to solutions of sodium chloride (NaCl), calcium chloride ($CaCl_2$), or magnesium chloride ($MgCl_2$), or to deionized water (DI water), which served as a control. Prior studies, which focused on the effect of deicing salts on concrete under wetting and drying, used solutions with either same weight of salt or same molar concentration. With either of these approaches, the concentration of ions, a measure of a solution's ice-melting properties, changes as function of the salt being used. For example, at the same molar concentration, $CaCl_2$ solution will have 50% more ions than NaCl solution. Another approach is based on keeping the molal ion concentration constant, which provides a fairer measure of comparison since it provides greater parity for comparisons. This approach was first used by Darwin et al. (2008). The molal ion concentration equals molality multiplied by the number of ions of solute. In the current study, the different salt solutions had the same molal ion concentration (8.55), equivalent to that of a 20% mass concentration of sodium chloride. The mixtures had *w/cm* ratios of either 0.38 or 0.44, and Grade 100 slag cement or Class C fly ash was used as the SCM at replacement percentages of 20%, 35%, or 50% based on the total volume of cementitious material. To ensure uniform distribution of the cementitious materials, SCMs were dry mixed with portland cement prior to batching. Table 2.2 lists the mixture proportions. The naming convention is as follows: 20%, 35%, or 50% represents the replacement percentage by volume of either slag cement (SL) or Class C fly ash (FA); Control mixtures incorporated 100% portland cement. The values 0.38 or 0.44 represent the *w/cm* ratio. Three concrete mixtures with a *w/cm* ratio of 0.44 (Control, 50% slag cement, and 50% Class C fly ash) used to determine the penetration depth of chloride ions. Table 2.3 summarizes the properties of the concrete mixtures.

Table 2.2: Mixture proportions (lb/yd^3)

Mixtures	*w/cm*	Cement	Class C fly ash	Grade 100 slag cement	Water	Sand	Pea gravel	Coarse aggregate		AEA+ (fl oz/yd^3)	HRWR* (fl oz/yd^3)
								A	B		
Control-0.44	0.44	556	0	0	245	1093	438	635	775	5.5	0.0
20% SL-0.44	0.44	452	0	100	243	1089	440	636	777	6.3	0.0
35% SL-0.44	0.44	369	0	180	242	1085	441	636	777	6.8	0.0
50% SL-0.44	0.44	286	0	260	240	1081	442	636	779	7.9	0.0
20% FA-0.44	0.44	454	95	0	242	1084	441	636	777	5.9	0.0
35% FA-0.44	0.44	374	168	0	238	1094	449	645	789	7.3	0.0
50% FA-0.44	0.44	292	244	0	236	1086	451	645	791	7.3	0.0
Control-0.38	0.38	604	0	0	230	1061	452	641	787	3.1	18.2
20% SL-0.38	0.38	491	0	108	228	1057	453	641	789	4.6	16.0
35% SL-0.38	0.38	401	0	196	227	1063	460	649	798	5.7	16.0
50% SL-0.38	0.38	310	0	281	225	1062	461	649	800	6.8	16.0
20% FA-0.38	0.38	488	107	0	226	1053	455	642	791	4.5	16.0
35% FA-0.38	0.38	405	182	0	223	1049	458	643	793	5.3	16.0
50% FA-0.38	0.38	317	265	0	221	1040	460	644	795	5.0	11.4

+ Air-entraining admixture
* High range water reducing admixture

Table 2.3: Concrete properties

Mixtures	*w/cm*	Air Content, %	Slump, in.	Temp., °F	Unit Wt., lb/ft^3	28-day Compressive Strength, psi
Control-0.44	0.44	6.50	3½	68	142.8	4950
Control-RE-0.44	0.44	8.00	4	68	139.7	4640
20% SL-0.44	0.44	6.75	2¾	70	142.7	4550
35% SL-0.44	0.44	6.50	3	70	142.5	4640
50% SL-0.44	0.44	6.50	2½	68	142.3	4970
50% SL-RE-0.44	0.44	8.00	4	68	140.2	5040
20% FA-0.44	0.44	7.50	4½	66	140.4	4340
35% FA-0.44	0.44	7.25	5½	65	140.5	4340
50% FA-0.44	0.44	6.50	6½	65	142.5	3640
50% FA-RE-0.44	0.44	6.75	7	66	143.3	4260
Control-0.38	0.38	6.50	2½	68	145.1	5360
20% SL-0.38	0.38	6.50	2	69	145.0	5370
35% SL-0.38	0.38	6.50	2	70	143.1	5860
50% SL-0.38	0.38	7.00	2¼	70	142.3	5470
20% FA-0.38	0.38	8.00	3½	70	140.4	5150
35% FA-0.38	0.38	8.00	5	70	141.8	4870
50% FA-0.38	0.38	7.25	6½	69	142.2	5080

2.3.3 Test Procedures

Twelve 12 × 3 × 3 in. (305 × 76 × 76 mm) specimens were cast for each concrete mixture using steel molds. The specimens were filled in two equal layers, and each layer was consolidated using a vibrating table with an amplitude of 0.006 in. (0.1 mm) and a frequency of 60 Hz for 15 to 30 seconds. The second layer was struck off with a 2 × 5½ in. (50 × 135 mm) steel screed. Two layers of wet burlap, soaked in water for 24 hours prior to casting, were placed on the surface of the concrete specimens, which were then covered by a 3.5-mil (89-µm) plastic sheet secured with rubber bands to prevent evaporation. After 6 ± 1 hour, the plastic was briefly removed and a water spray bottle was used to wet the burlap. Specimens were demolded after 24 hours and submerged for curing in lime-saturated water. After 28 days of curing, specimen mass and the transverse frequency, as determined by the impact resonance test from ASTM C215 (Figure 2.2), were measured to determine the initial dynamic modulus. Then specimens were moved to an environmentally-controlled room with a relative humidity of 50 ± 4 percent and temperature of 73 ± 3 ºF (23 ± 2 ºC), where they dried for 14 days in preparation for testing.

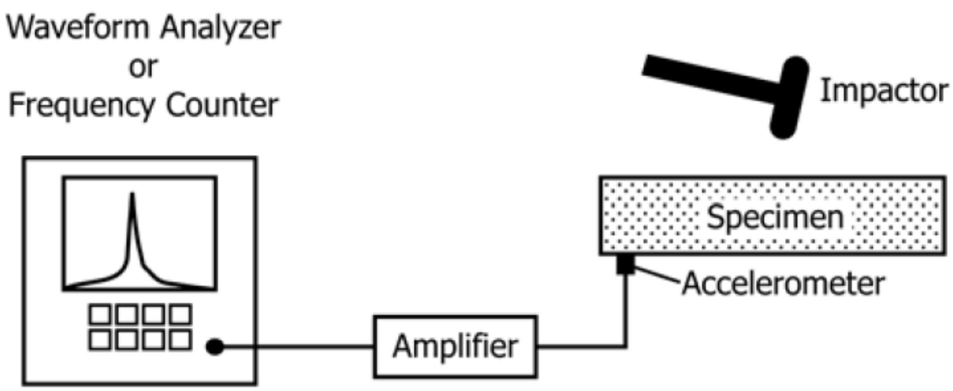

Figure 2.2: Representation of the Impact Resonance Test (ASTM C215)

The 12 specimens in each batch were separated into four sets of three. The sets were submerged in deionized water or one of the salt solutions, NaCl, $CaCl_2$, or $MgCl_2$, as shown in Figure 2.3. The specimens were exposed to wetting and drying cycles in which the wetting phase consisted of submerging the specimens for 17 ± 1 hour at 39.2 ºF (4 ºC), followed by the drying phase for 7 ± 1 hour at 73 ± 3 ºF (23 ± 2 ºC) and a relative humidity of 50 ± 4 percent. The exposure conditions were chosen to ensure the formation of the calcium oxychloride, which is controlled by the concentration of the salt and temperature, as described in Section 2.1.

Figure 2.3: Concrete specimens (wetting phase)

Every 14 cycles, the mass and transverse frequency of the specimens were measured at the end of a wetting phase and the dynamic moduli of elasticity were calculated in accordance with ASTM C215. Deionized (DI) water and salt solutions were also changed every 14 cycles. The ratio of the dynamic modulus at any cycle to the initial dynamic modulus is defined as the relative dynamic modulus of elasticity. The testing continued for 300 cycles, after which the specimens were evaluated visually. After 150 cycles, additional specimens from the three concrete mixtures were broken and sprayed with a 0.0141N silver nitrate solution to determine the depth of the penetration of chloride ions.

2.4 EXPERIMENTAL RESULTS AND DISCUSSION

The change in the average relative dynamic modulus of elasticity of the specimens was used a measure to the effect of the deicing chemicals on the concrete mixtures. The specimens were exposed to DI water and solutions of NaCl, $CaCl_2$, or $MgCl_2$. Appendix A shows the mass, frequency, and dynamic moduli of elasticity for the specimens, and the coefficient of variation for each three-specimen set. Because the initial dynamic modulus was determined at the end of the curing period (28 days) and the specimens were then dried for 14 days, a decrease in the dynamic modulus was observed after the first 14 cycles of wetting and drying. The decrease is likely due to drying that was not fully compensated for during the first 14 wetting and drying cycles.

Evaluating the effect of some of the parameters on the damage due to wetting and drying was achieved by using Student's t-test, which is used to examine the statistical significance of differences in specimen behavior. In this study, if the *p*-value (the probability that the observed difference in means is due to random variation rather than a meaningful difference in behavior) is less than or equal to 0.05, the difference between results is considered to be statistically significant.

Table 2.4 summarizes the findings of this study, which are described in detail in the following sections. The table shows the average relative dynamic modulus of elasticity at 300 cycles for specimens exposed to deionized water (DI water) or the salt solutions. Yellow shading indicates that the specimens exhibited spalling. Specimens exposed to DI water or NaCl, regardless of the concrete mixture and the *w/cm* ratio, showed no signs of deterioration and an increase in relative dynamic modulus. Some specimens exposed to the $CaCl_2$ or $MgCl_2$ solutions exhibited spalling, and all, except the mixtures incorporating a 50% replacement of portland cement with Class C fly ash, exhibited a decrease in the relative dynamic modulus of elasticity. The specimens that exhibited spalling were those incorporating 100% portland cement exposed to either the $CaCl_2$ or $MgCl_2$ solutions and those incorporating 20% of either slag cement or Class C fly ash as replacements for portland cement exposed to the $CaCl_2$ solution. Based on these observations, the mixtures that exhibited no spalling after 300 cycles of wetting and drying with solutions of $CaCl_2$ or $MgCl_2$ are considered to be durable under conditions that result in the formation of calcium oxychloride. Details follow.

Table 2.4: Average relative dynamic modulus of elasticity at 300 cycles

	Solutions			
Mixture	DI water	NaCl	$CaCl_2$	$MgCl_2$
Control-0.38	1.05	1.02	0.68	0.86
20% SL-0.38	1.05	1.03	0.89	0.96
35% SL-0.38	1.05	1.03	0.97	0.97
50% SL-0.38	1.05	1.03	0.99	0.98
20 % FA-0.38	1.06	1.02	0.92	0.96
35 % FA-0.38	1.07	1.04	0.97	0.95
50 % FA-0.38	1.08	1.05	1.00	0.96
Control-0.44	1.06	1.03	0.53	0.85
20% SL-0.44	1.04	1.03	0.87	0.94
35% SL-0.44	1.05	1.03	0.94	0.95
50% SL-0.44	1.04	1.02	0.96	0.95
20 % FA-0.44	1.06	1.04	0.90	0.92
35 % FA-0.44	1.09	1.05	0.99	0.95
50 % FA-0.44	1.13	1.08	1.00	0.97

Highlighted values indicate spalling

2.4.1 Effect of Deionized Water on Specimens Exposed to Wetting and Drying

Figures 2.4 and 2.5 show the average relative dynamic modulus of elasticity of specimens exposed to DI water versus the number of cycles of testing for concrete mixtures with *w/cm* ratios of 0.38 and 0.44, respectively. As shown in these figures, the average relative dynamic modulus of elasticity increased for all concrete mixtures regardless of the *w/cm* ratio. The increase in the average relative dynamic modulus of elasticity occurred due to an increase in both the degree of hydration and the level of saturation. The specimens for mixtures with 50% Class C fly ash for both *w/cm* ratios had the highest increase in the average relative dynamic modulus. This is likely due to the low initial stiffness of the concrete caused by the relatively slow pozzolanic reaction of fly ash. Figures B1 to B4 in Appendix B show the specimens exposed to DI water after 300 cycles. No signs of damage were observed on any specimens.

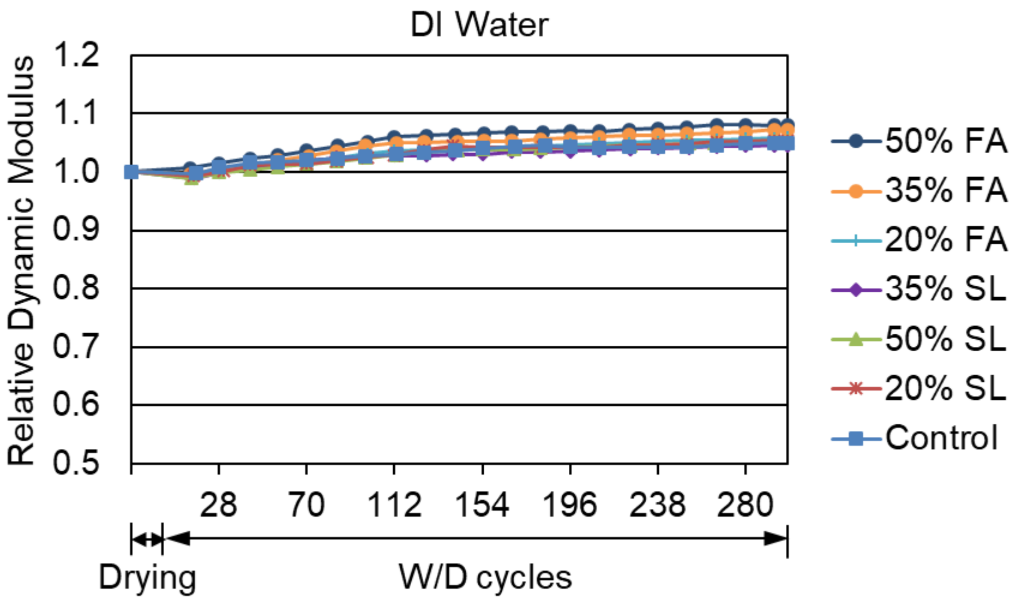

Figure 2.4: Relative dynamic modulus of elasticity vs. number of wet-dry (W/D) cycles for concrete specimens with *w/cm* = 0.38 exposed to deionized (DI) water

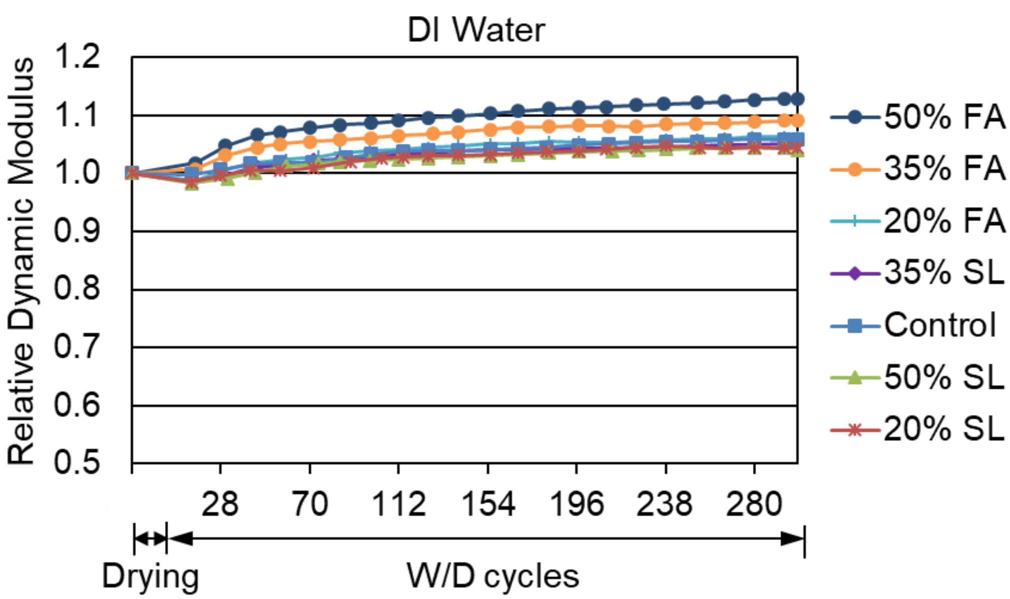

Figure 2.5: Average relative dynamic modulus of elasticity vs. number of wet-dry (W/D) cycles for concrete specimens with *w/cm* = 0.44 exposed to deionized (DI) water

2.4.2 Effect of NaCl on Specimens Exposed to Wetting and Drying

The average relative dynamic modulus of elasticity versus the number of wet-dry cycles for specimens exposed to NaCl is shown in Figures 2.6 and 2.7 for mixtures with *w/cm* ratios of

0.38 and 0.44, respectively. As shown in the figures, the average relative dynamic modulus increased for all specimens. Furthermore, after 300 cycles, no signs of deterioration were observed for any of the mixtures, as shown in Figures 2.8 to 2.11.

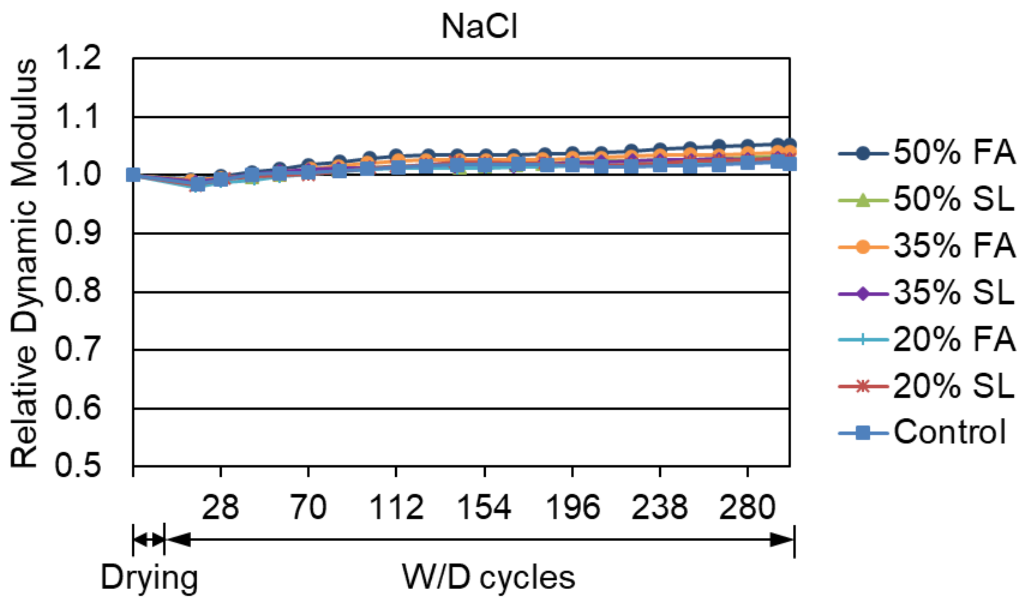

Figure 2.6: Average relative dynamic modulus of elasticity vs. number of wet-dry (W/D) cycles for concrete specimens with *w/cm* = 0.38 exposed to NaCl solution

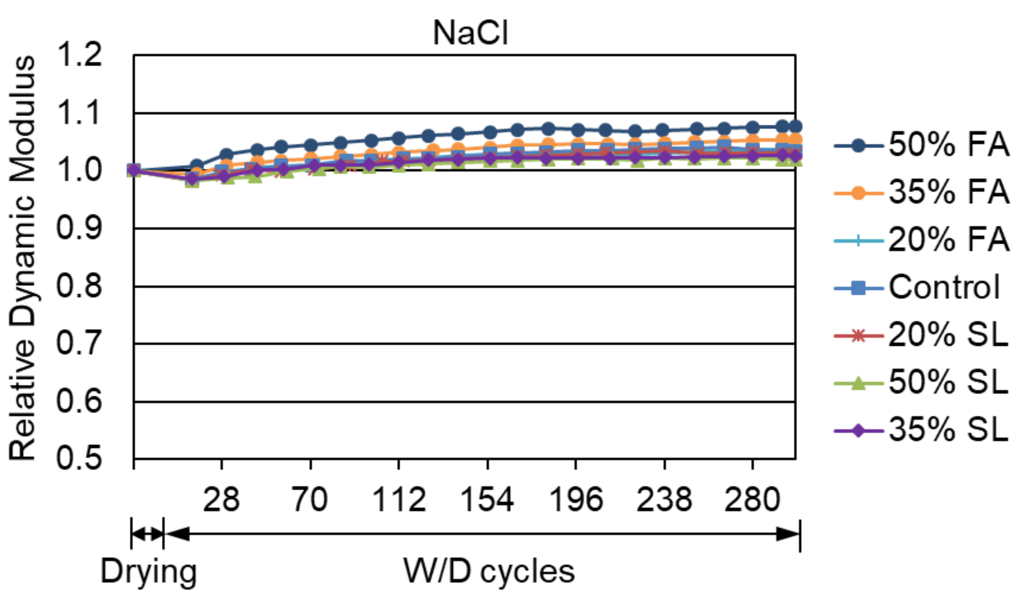

Figure 2.7: Average relative dynamic modulus of elasticity vs. number of wet-dry (W/D) cycles for concrete specimens with *w/cm* = 0.44 exposed to NaCl solution

(a) Control (100% portland cement, 0% slag cement) | (b) 20% slag cement | (c) 35% slag cement | (d) 50% slag cement

Figure 2.8: Specimens for concrete mixtures with *w/cm* of 0.38 containing slag cement exposed to NaCl solution at 300 cycles

(a) Control (100% portland cement, 0% fly ash) | (b) 20% fly ash | (c) 35% fly ash | (d) 50% fly ash

Figure 2.9: Specimens for concrete mixtures with *w/cm* of 0.38 containing Class C fly ash exposed to NaCl solution at 300 cycles

(a) Control (100% portland cement, 0% slag cement)
(b) 20% slag cement
(c) 35% slag cement
(d) 50% slag cement

Figure 2.10: Specimens for concrete mixtures with *w/cm* of 0.44 containing slag cement exposed to NaCl solution at 300 cycles

(a) Control (100% portland cement, 0% fly ash)
(b) 20% fly ash
(c) 35% fly ash
(d) 50% fly ash

Figure 2.11: Specimens for concrete mixtures with *w/cm* of 0.44 containing Class C fly ash exposed to NaCl solution at 300 cycles

2.4.3 Effect of $CaCl_2$ on Specimens Exposed to Wetting and Drying

The average relative dynamic modulus of elasticity versus the number of wet-dry cycles for specimens exposed to $CaCl_2$ is shown in Figures 2.12 and 2.13 for mixtures with *w/cm* ratios of 0.38 and 0.44, respectively. Regardless of the *w/cm* ratio, the results show that specimens with 100% portland cement (Control) exhibited a significant decrease in the average relative dynamic modulus. For Control mixtures with a *w/cm* of 0.38, the average relative dynamic modulus decreased below 0.90 after 56 cycles and reached 0.68 at 300 cycles. Increasing the *w/cm* ratio to 0.44 further reduced performance; the average relative dynamic modulus decreased below 0.90 after 42 cycles and reached 0.53 at 300 cycles. At the end of the test, the Control specimens showed significant deterioration, as shown in Figure 2.14.

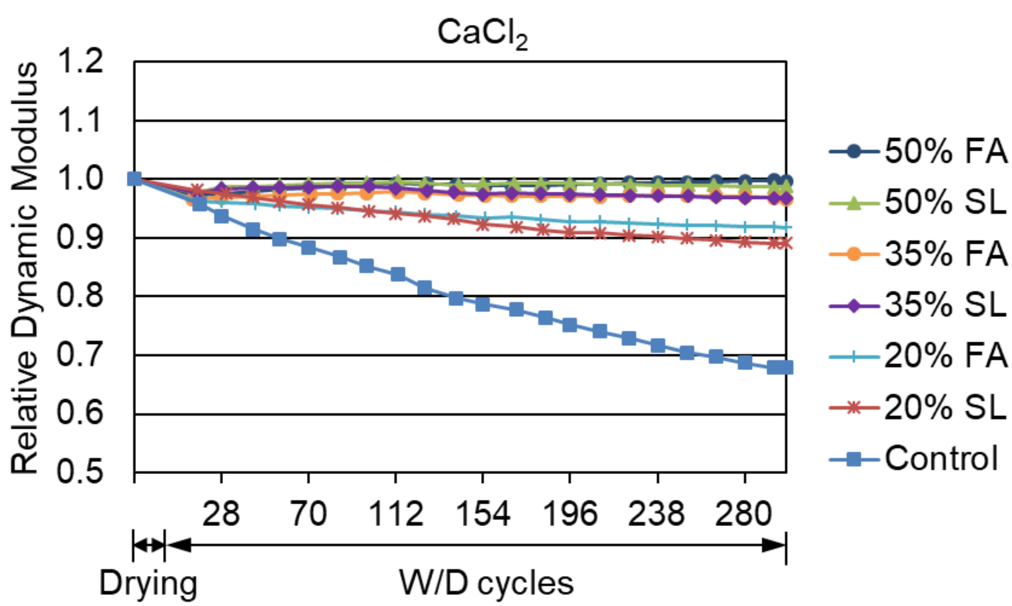

Figure 2.12: Average relative dynamic modulus of elasticity vs. number of wet-dry (W/D) cycles for concrete specimens with *w/cm* = 0.38 exposed to $CaCl_2$ solution

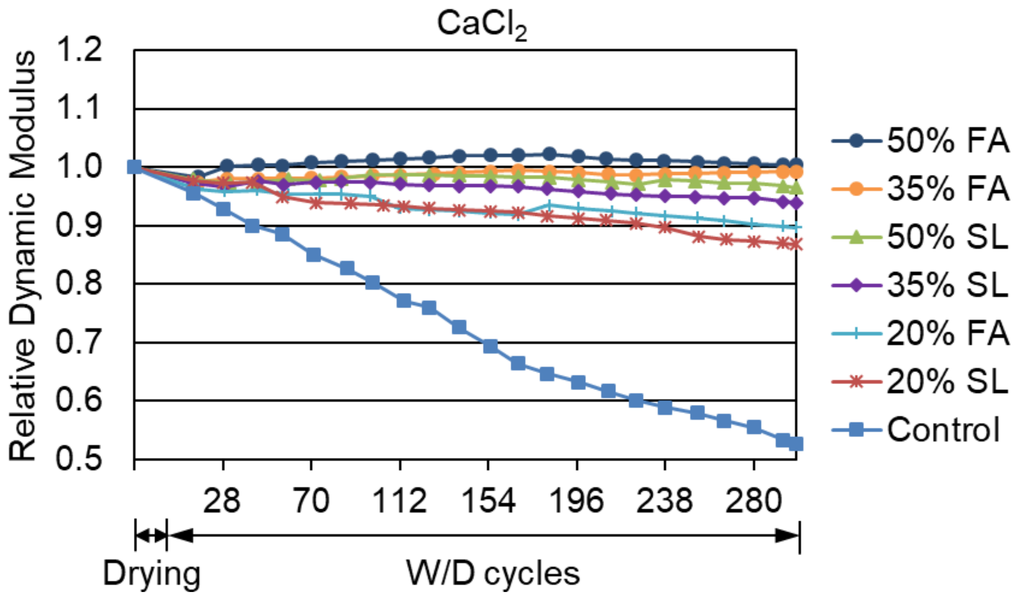

Figure 2.13: Average relative dynamic modulus of elasticity vs. number of wet-dry (W/D) cycles for concrete specimens with *w/cm* = 0.44 exposed to $CaCl_2$ solution

(a) *w/cm* = 0.38 (b) *w/cm* = 0.44

Figure 2.14: Specimens of Control mixtures (100% portland cement) exposed to $CaCl_2$ solution at 300 cycles

Replacing 20% of the portland cement with slag cement for both *w/cm* ratios had a positive effect on the performance compared to that of the Control mixtures. The specimens cast with 20% slag, however, still did not reach 300 cycles without damage; the average relative dynamic modulus dropped below 0.90 after 238 cycles at both *w/cm* ratios and reached 0.89 and 0.87 at 300 cycles for specimens with *w/cm* ratios of 0.38 or 0.44, respectively. At the end of the test, some spalling at the edges of the specimens was observed, as shown in Figure 2.15.

(a) *w/cm* = 0.38 (b) *w/cm* = 0.44

Figure 2.15: Specimens of mixtures incorporating 20% slag cement exposed to $CaCl_2$ solution at 300 cycles

Increasing the slag cement replacement to 35% or 50% further improved performance. At 300 cycles, the average relative dynamic moduli were 0.97 and 0.99 for specimens with a *w/cm* ratio of 0.38 and 35% or 50% slag cement, respectively; at a *w/cm* of 0.44, the average relative dynamic moduli at 300 cycles were 0.94 and 0.96 for specimens with 35% or 50% slag cement, respectively. At the end of testing, no signs of deterioration were observed for specimens with 35% or 50% slag cement replacements of portland cement, as shown in Figure 2.16.

(a) 35% slag cement *w/cm* = 0.38

(b) 35% slag cement *w/cm* = 0.44

(c) 50% slag cement *w/cm* = 0.38

(d) 50% slag cement *w/cm* = 0.44

Figure 2.16: Specimens for concrete mixtures containing slag cement exposed to CaCl2 solution at 300 cycles

The positive effect of slag cement on the resistance of concrete specimens is likely due to differences between the chemical composition of slag cement and portland cement. As illustrated in Table 2.1; the ratio of calcium oxide (CaO) to silicon dioxide (SiO_2) is much lower for slag cement (1.2) than for portland cement (3.0). Therefore, using slag cement reduces the quantity of $Ca(OH)_2$, which reduces the amount of calcium oxychloride formed under exposure to $CaCl_2$ or $MgCl_2$. By increasing the replacement percentage of slag cement to 35% or 50%, the amount of $Ca(OH)_2$ is further reduced, resulting in more durable concrete.

Replacing 20% of the portland cement with Class C fly ash also improved the performance compared with the Control mixtures, more so than for concrete with 20% slag cement. The average relative dynamic moduli after 300 cycles were 0.92 and 0.90 for specimens with *w/cm* ratios of

0.38 and 0.44, respectively. In spite of the improved performance, some spalling at the edges of the specimens was still observed after testing, as shown in Figure 2.17.

(a) *w/cm* = 0.38 (b) *w/cm* = 0.44

Figure 2.17: Specimens of mixtures incorporating 20% Class C fly ash exposed to $CaCl_2$ solution at 300 cycles

Increasing the fly ash replacement to 35% or 50% resulted in further improvements in performance. At 300 cycles, the average relative dynamic moduli were 0.97 and 1.00 for specimens with a *w/cm* ratio of 0.38 and including 35% or 50% Class C fly ash, respectively; 0.99 and 1.00 for specimens with a *w/cm* ratio of 0.44 and including 35% or 50% Class C fly ash, respectively. Visual inspection showed no damage after 300 cycles for specimens with 35% or 50% Class C fly ash replacements, as shown in Figures 2.18.

(a) 35% fly ash w/cm = 0.38 (b) 35% fly ash w/cm = 0.44 (c) 50% fly ash w/cm = 0.38 (d) 50% fly ash w/cm = 0.44

Figure 2.18: Specimens for concrete mixtures containing Class C fly ash exposed to $CaCl_2$ solution at 300 cycles

Based on the average relative dynamic modulus of elasticity, specimens with Class C fly ash exhibited better performance than specimens with slag cement. For specimens incorporating 20% SCM with *w/cm* ratios of 0.38 and 0.44, using Class C fly ash resulted in a 3% increase in the average relative dynamic moduli (at the end of the test) compared to using slag cement. This improvement in performance is also apparent when comparing the appearance of specimens containing a 20% replacement of portland cement with Class C fly ash (Figure 2.17) with those containing a 20% replacement of portland cement with slag cement (Figure 2.15). Also, at higher replacement percentages (35% and 50% of portland cement with SCMs), specimens incorporating Class C fly ash showed better performance than those incorporating the same replacement percentages of slag cement, especially with *w/cm* of 0.44. At the end of the test (300 cycles), 6% and 4% increases in the average relative dynamic moduli were obtained for specimens incorporating 35% and 50% Class C fly ash compared to specimens incorporating the same replacement percentages of slag cement. Student's t-test shows that the differences in the relative dynamic moduli after 300 cycles between specimens with slag cement and specimens with Class C fly ash are statistically significant ($p = 1.56\times10^{-4}$ and 3.97×10^{-2}), except for the mixtures with 35% SCM and a *w/cm* ratio of 0.38.

The more positive effect of Class C fly ash compared to slag cement on the resistance of concrete exposed to $CaCl_2$ can be attributed to the lower ratio of calcium oxide (CaO) to silicon dioxide (SiO_2) – 0.9 for Class C fly ash versus and 1.2 for slag cement – resulting in greater pozzolanic action and a greater reduction in the quantity of $Ca(OH)_2$ with Class C fly ash, leading to the production of less calcium oxychloride.

Increasing replacement the percentage for either slag cement or Class C fly ash from 20% to 35% resulted in an increase in the average relative dynamic modulus ranging from 5% to 10%, while increasing replacement percentage for either SCM from 35% to 50% resulted in an increase of only 1% to 3%. Specimens incorporating 20% with either SCM exhibited some spalling, as shown in Figures 2.15 and 2.17, while specimens are incorporating 35% or 50% with either SCM exhibited no damage, as shown in Figures 2.16 and 2.18. Based on the acceptance criteria, replacing 20% of portland cement with SCMs was not sufficient to produce durable concrete, while replacing 35% or 50% of portland cement with SCMs was. Replacement percentages of SCMs between 20% and 35%, which were not incorporated in the current study, may also be sufficient.

2.4.4 Effect of $MgCl_2$ on Specimens Exposed to Wetting and Drying

The average relative dynamic modulus of elasticity versus the number of wet-dry cycles for specimens exposed to $MgCl_2$ is shown in Figures 2.19 and 2.20 for mixtures with *w/cm* ratios of 0.38 and 0.44, respectively. The results show that specimens with 100% portland cement with either *w/cm* ratio exhibited a reduction in the average relative dynamic modulus at a slower rate than when exposed to $CaCl_2$. This finding is in line with the observations by Jain et al. (2012) who found that $MgCl_2$ required more time than $CaCl_2$ to cause microstructural cracking for concrete specimens with 100% portland cement.

The reaction between $MgCl_2$ and $Ca(OH)_2$, as shown in Eq. (2.3) (Section 2.1) leads to the formation of magnesium hydroxide $Mg(OH)_2$ (brucite) and liberation of $CaCl_2$. Magnesium hydroxide $Mg(OH)_2$ is relatively impermeable and should restrict solution ingress into concrete (Farnam et al. 2015b). This effect is evaluated later in this section. In addition, Qiao et al. (2018b) found that the formation of calcium oxychloride due to exposure to $MgCl_2$ is dependent on the molar ratio of $Ca(OH)_2$ to $MgCl_2$. Theoretically, calcium oxychloride can be formed only if the molar ratio is greater than 1.0. If the molar ratio of $Ca(OH)_2$ to $MgCl_2$ equal or less than 1.0, $Ca(OH)_2$ will react with $MgCl_2$ to form $Mg(OH)_2$, as shown in Eq. (2.3), reducing the quantity of $Ca(OH)_2$ available to react with $CaCl_2$ to form calcium oxychloride [Eq. (2.1)]. Thus, the formation of $Mg(OH)_2$ causes both a reduction in the ingress of solution into concrete and consumption of $Ca(OH)_2$, which reduces the quantity of calcium oxychloride, slowing the rate of damage for concrete exposed to $MgCl_2$.

For the 100% portland cement concrete at a *w/cm* of 0.38, the average relative dynamic modulus decreased below 0.90 after 170 cycles and reached 0.86 at 300 cycles. For a *w/cm* ratio to 0.44, the average relative dynamic modulus dropped below 0.90 after 238 cycles, with a value of 0.85 at 300 cycles. At the end of the test, the specimens exhibited some spalling, as shown in Figure 2.21.

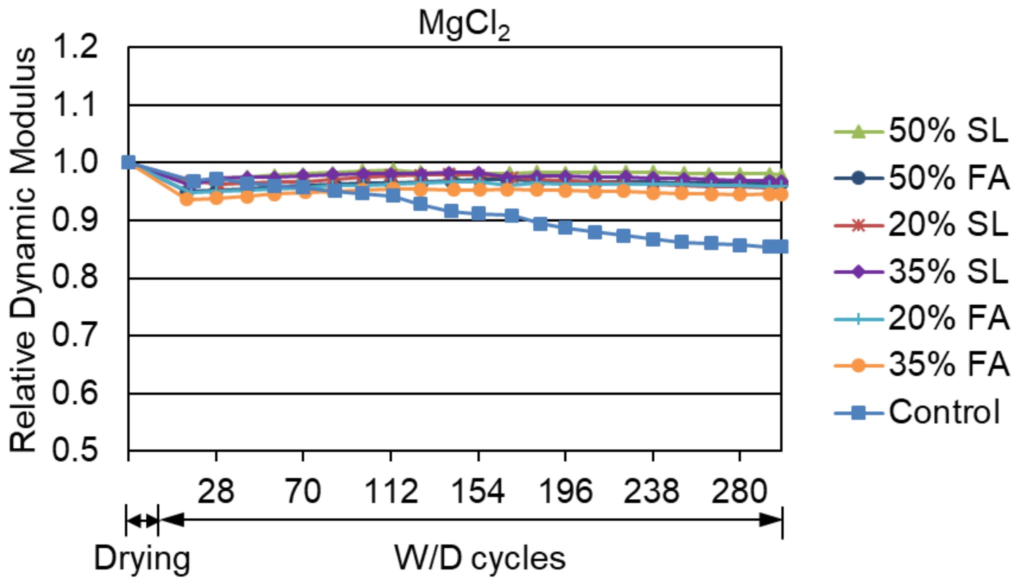

Figure 2.19: Average relative dynamic modulus vs. number of wet-dry (W/D) cycles of elasticity for concrete specimens with *w/cm* = 0.38 exposed to $MgCl_2$ solution

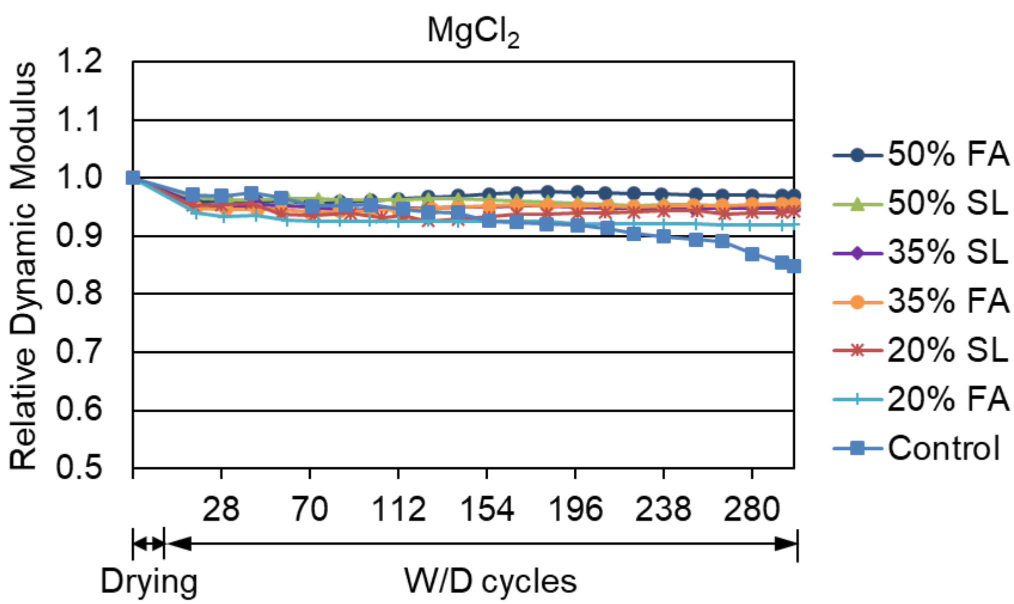

Figure 2.20: Average relative dynamic modulus of elasticity vs. number of wet-dry (W/D) cycles for concrete specimens with *w/cm* = 0.44 exposed to $MgCl_2$ solution

(a) *w/cm* = 0.38 (b) *w/cm* = 0.44

Figure 2.21: Specimens of Control mixtures (100% portland cement) exposed to $MgCl_2$ solution at 300 cycles

Replacing 20%, 35%, or 50% of the portland cement with either slag cement or Class C fly ash for mixtures with either *w/cm* ratio resulted in noticeable improvements compared to mixtures with 100% portland cement, with no visible damage after 300 cycles, as shown in Figures 2.22 to 2.25. For a *w/cm* ratio of 0.38, the average relative dynamic moduli at 300 cycles were 0.96, 0.97 and 0.98 for specimens with 20%, 35% or 50% slag cement and 0.96, 0.95 and 0.96 for specimens with 20%, 35% or 50% Class C fly ash. For a *w/cm* ratio of 0.44, the average relative dynamic moduli at 300 cycles were 0.94, 0.95 and 0.95 for specimens with 20%, 35% or 50% slag cement and 0.92, 0.95 and 0.97 for specimens with 20%, 35% or 50% Class C fly ash.

(a) 20% slag cement (b) 35% slag cement (c) 50% slag cement

Figure 2.22: Specimens for concrete mixtures with *w/cm* of 0.38 containing slag cement exposed to $MgCl_2$ solution at 300 cycles

(a) 20% slag cement (b) 35% slag cement (c) 50% slag cement

Figure 2.23: Specimens for concrete mixtures with *w/cm* of 0.44 containing slag cement exposed to $MgCl_2$ solution at 300 cycles

(a) 20% fly ash (b) 35% fly ash (c) 50% fly ash

Figure 2.24: Specimens for concrete mixtures with *w/cm* of 0.38 containing Class C fly ash exposed to $MgCl_2$ solution at 300 cycles

(a) 20% fly ash (b) 35% fly ash (c) 50% fly ash

Figure 2.25: Specimens for concrete mixtures with *w/cm* of 0.44 containing Class C fly ash exposed to $MgCl_2$ solution at 300 cycles

Specimens for mixtures incorporating 20% slag cement or Class C fly ash had no signs of damage at the end of the test. For a *w/cm* ratio of 0.38, the average relative dynamic modulus at

300 cycles was 0.96 for specimens with 20% slag cement or Class C fly ash. For a *w/cm* ratio of 0.44, the average relative dynamic moduli at 300 cycles were 0.94 and 0.92 for specimens with 20% slag cement and Class C fly ash, respectively. Increasing the replacement percentage of either slag cement or Class C fly ash above 20% resulted in small changes in the average relative dynamic modulus, as shown in Table 2.4 and Figures 2.19 and 2.20, with most changes in the relative modulus equal to 2% or less; the mixtures with a *w/cm* ratio of 0.44 containing Class C fly ash were the exception, with relative dynamic moduli of 0.95 and 0.97 for the mixtures containing 35% and 50% replacements, respectively. Regardless of the replacement percentages, specimens with either slag cement or Class C fly ash showed no spalling at the end of the test, as shown in Figures 2.22 to 2.25. Based on the acceptance criteria, using SCMs at 20%, 35%, or 50% replacement of portland cement was sufficient to produce durable concrete under exposure to $MgCl_2$.

Magnesium hydroxide $Mg(OH)_2$ is formed from a reaction between $MgCl_2$ and $Ca(OH)_2$, as described in Section 2.1. $Mg(OH)_2$ is relatively impermeable. Its presence on the exterior of the specimens should limit the ingress of liquids into the concrete, which could be one of the reasons behind the slower rate of damage for the specimens exposed to $MgCl_2$. To evaluate this effect, three concrete mixtures were chosen to be recast and tested, as described in Section 2.3.2, to determine the depth of penetration of chloride ions.

The Control specimens and those with 50% slag cement and 50% Class C fly ash replacement of portland cement subjected to just 150 cycles were used to determine the depth of penetration of chloride ions. The specimens were cast with a *w/cm* ratio of 0.44. After 150 cycles, the specimens were broken and the newly exposed interior concrete was sprayed with a 0.0141N silver nitrate solution, which can be recognized by the whitish color of silver chloride (AgCl), which forms due to the reaction between silver nitrate ($AgNO_3$) and chloride ions. Figures 2.26, 2.27, and 2.28 show the depth of chloride ion penetration inside the specimens for each of the three deicing salts used in the test. In these figures, the whitish color (lighter regions) indicates the presence of AgCl, while the darker regions inside the red circles (dashed lines) indicate that chloride ions had not penetrated.

(a) NaCl (b) $CaCl_2$ (c) $MgCl_2$

Figure 2.26: Chloride ion penetration for specimens of Control concrete mixture with *w/cm* ratio of 0.44 (at 150 cycles); the whitish color (lighter region) indicates that chloride ions had penetrated, while the darker regions inside the red circles (dashed lines) indicate that chloride ions had not penetrated

(a) NaCl (b) $CaCl_2$ (c) $MgCl_2$

Figure 2.27: Chloride ion penetration for specimens of concrete mixture with 50% slag cement with *w/cm* ratio of 0.44 (at 150 cycles); the whitish color (lighter region) indicates that chloride ions had penetrated, while the darker regions inside the red circles (dashed lines) indicate that chloride ions had not penetrated

(a) NaCl (b) $CaCl_2$ (c) $MgCl_2$

Figure 2.28: Chloride ion penetration for specimens of concrete mixture with 50% Class C fly ash with *w/cm* ratio of 0.44 (at 150 cycles); the whitish color (lighter region) indicates that chloride ions had penetrated, while the darker regions inside the red circles (dashed lines) indicate that chloride ions had not penetrated

For the Control (100% portland cement) and 50% Class C fly ash specimens exposed to NaCl, Figures 2.26a and 2.28a show, respectively, that chloride ions fully penetrated the specimens, while for the 50% slag cement specimen, Figure 2.27a shows that chloride ions penetrated approximately one-half of the specimen's dimension. For specimens exposed to $CaCl_2$, chloride ions penetrated throughout the Control specimen, as shown in Figure 2.26b, and through most of the 50% Class C fly ash specimen, as shown in Figure 2.28b, while the specimen with 50% slag cement has much less penetration, as shown in Figure 2.27b. Regardless of the concrete mixture, exposure to $MgCl_2$ did not result in chloride ion penetration through the full depth of the specimens, as shown in Figures 2.26c, 2.27c, and 2.28c. In all cases, the depth of chloride ion penetration was lower in specimens exposed to $MgCl_2$ than in specimens exposed to NaCl or $CaCl_2$, suggesting that brucite [magnesium hydroxide $Mg(OH)_2$] had formed in the specimens and impeded chloride ion ingress.

2.4.5 Effect of Replacement Percentage of Slag Cement and Class C Fly Ash on the Damage Due to Wetting and Drying

Replacing portland cement with an SCM (slag cement or Class C fly ash) resulted in improved resistance to damage due to exposure to $CaCl_2$ or $MgCl_2$, under wetting and drying cycles. Figures 2.29 and 2.30 show the increase in the average relative dynamic modulus at 300 cycles for specimens incorporating SCMs compared to specimens with 100% portland cement and exposed to $CaCl_2$ and $MgCl_2$, respectively.

For specimens exposed to $CaCl_2$, replacing portland cement with 20%, 35%, or 50% slag cement or Class C fly ash results in an increase in the average relative dynamic modulus ranging from 31% to 91%, as shown in Figure 2.29. For specimens exposed to $MgCl_2$, replacing portland cement with 20%, 35%, or 50% slag cement or Class C fly ash results in an increase in the average relative dynamic modulus ranging from 8% to 15%, as shown in Figure 2.30.

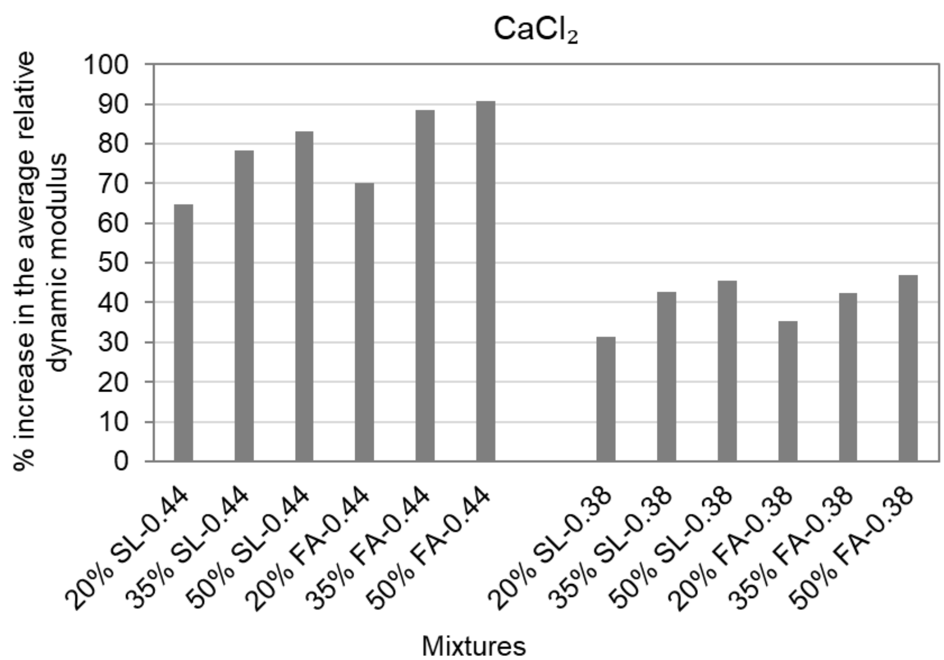

Figure 2.29: Increase in the average relative dynamic modulus at 300 cycles for specimens with SCMs relative to those of specimens with 100% portland cement vs. replacement percentage of SCM for specimens exposed to $CaCl_2$

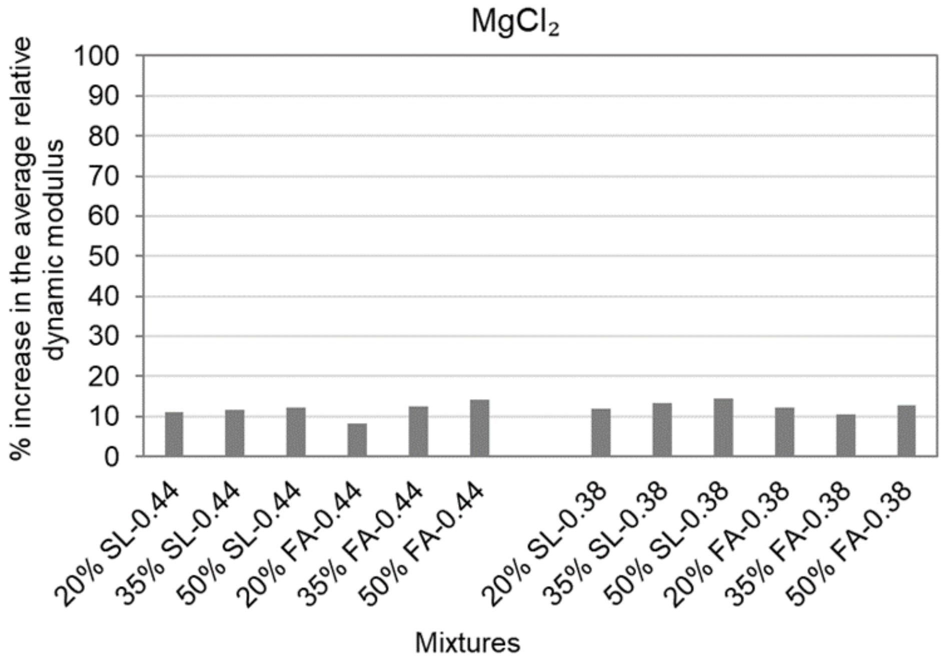

Figure 2.30: Increase in the average relative dynamic modulus at 300 cycles for specimens with SCMs relative to those of specimens with 100% portland cement vs. replacement percentage of SCM for specimens exposed to $MgCl_2$

Student's t-test shows that the differences in the relative dynamic moduli after 300 cycles between specimens with SCMs and specimens with 100% portland cement under exposure to $CaCl_2$ or $MgCl_2$ are statistically significant (p = 1.76×10^{-8} and 1.02×10^{-3}). This finding is in line with prior studies (Jain et al. 2012, Suraneni et al. 2016, Ghazy and Bassuoni 2017).

Specimens for the Control mixture (100% portland cement) exposed to $CaCl_2$ exhibit significant damage, as shown in Figure 2.14. The specimens with 20% slag cement or Class C fly ash, exhibit some spalling at the edges, but far less damage overall, as shown in Figures 2.15 and 2.17, and the specimens with cement replacements of 35% or 50% slag cement or Class C fly ash show no signs of deterioration, as shown in Figure 2.16 and 2.18.

For the specimens exposed to $MgCl_2$, replacing portland cement with slag cement or Class C fly ash also resulted in improved resistance to damage. While the Control specimens with *w/cm* ratios of 0.38 or 0.44 exhibited some spalling, as shown in Figure 2.21, no damage was observed for specimens incorporating 20%, 35%, or 50% slag cement or Class C fly ash for either *w/cm* ratio, as shown in Figures 2.22 to 2.25.

Based on the acceptance criteria tied to Table 2.4, using SCMs as a 20% replacement of portland cement was not sufficient to produce durable concrete under conditions that result in the formation of calcium oxychloride, while using SCMs as 35% or 50% as replacements was. Replacement percentages between 20% and 35%, which were not included in the current study, may also be sufficient. Increasing the replacement percentage from 35% to 50% resulted in only a slight increase in the average relative dynamic moduli (1% to 3%). Using SCMs as a 50% replacement of portland cement has resulted in another durability issue, scaling, as described in Chapter 3. Therefore, replacing portland cement with more than a 35% SCM replacement of portland cement will not be recommended.

2.4.6 Effects of *w/cm* Ratio on the Damage Due to Wetting and Drying

Evaluating the effect of *w/cm* ratio on the damage due to wetting and drying is achieved using Student's t-test. Tables A.70 and A.71 in Appendix A shows the results from the Student's t-test for all comparisons.

As shown in Sections 2.4.1 and 2.4.2, no damage was observed on any specimen exposed to DI or NaCl, regardless of *w/cm* ratio. Reducing the *w/cm* ratio, however, had a measurable effect on the average relative dynamic modulus for specimens with 100% portland cement exposed to $CaCl_2$ solution, with an average increase of 29% at 300 cycles as the *w/cm* ratio decreased from 0.44 to 0.38, a difference that is statistically significant ($p = 1.91\times10^{-4}$). This trend is not observed, however, for concrete containing SCMs.

2.5 SUMMARY AND CONCLUSIONS

In this study, 14 concrete mixtures (204 specimens) were studied to evaluate the damage in concrete subjected to cycles of wetting and drying while exposed to deicing salts. The study evaluates the effects of deicing salt type (NaCl, $CaCl_2$, or $MgCl_2$), water-to-cementitious material ratio (0.38 or 0.44), and percentage replacement of cement with SCMs (slag cement or Class C fly ash) (20%, 35%, or 50% by volume of cement) on damage.

The following conclusions based on the relative dynamic modulus, visual inspection, and chloride ion penetration described in this chapter.

1. Based on average relative dynamic modulus and visual inspection at 300 cycles, exposure to deionized water or NaCl did not cause deterioration to concrete.
2. $CaCl_2$ caused more damage and reduction in the average relative dynamic modulus than the other deicing salts for concrete specimens with 100% portland cement. $MgCl_2$ also resulted in damage for concrete specimens with 100% portland cement, but less so than $CaCl_2$.
3. Increasing the replacement percentage of portland cement with slag cement or Class C fly ash resulted in increased resistance of concrete to $CaCl_2$ or $MgCl_2$. This improvement can be tied to the reduction in available $Ca(OH)_2$ obtained through the use of these two supplementary cementitious materials, which, in turn, reduces the quantity of calcium oxychloride formed at lower temperatures.
4. Based on the acceptance criteria, replacing 20% of portland cement with SCMs is not sufficient to produce durable concrete under conditions that result in the formation of calcium oxychloride, while replacing 35% or 50% of portland cement with SCMs is.

5. Increasing the replacement percentage from 35% to 50% results in only a slight increase in the average relative dynamic moduli (1% to 3%). On the other hand, using SCMs as a 50% replacement of portland cement causes scaling, as shown in Chapter 3. Therefore, using SCM replacements of portland cement in access of 35% is not recommended.
6. Chloride ions do not penetrate as far into the concrete when concrete is exposed to $MgCl_2$ as when concrete is exposed to $CaCl_2$ or NaCl, suggesting that magnesium hydroxide $Mg(OH)_2$ (brucite), which has low permeability, forms in the specimens.
7. Reducing the *w/cm* ratio did not have a clear impact on the damage of concrete containing SCMs due to exposure to the wetting and drying cycles but is effective at reducing damage to concrete with portland cement as the only binder. A *w/cm* ratio as low as 0.38 in concrete with portland cement as the only binder, however, is not adequate to produce durable concrete under conditions that result in the formation of calcium oxychloride.

CHAPTER 3 - SCALING RESISTANCE OF CONCRETE CONTAINING SLAG CEMENT OR CLASS C FLY ASH

3.1 INTRODUCTION

During winter, deicing salts (such as sodium chloride, calcium chloride, and magnesium chloride) are used to melt ice and snow to make roads safe for motor vehicles. Using these salts, however, can cause damage to the surface of the concrete due to scaling, as described in Chapter 1. Concrete incorporating supplementary cementitious materials (SCMs) such as slag cement, fly ash, and silica fume has been used to improve durability by controlling the alkali-silica reaction, improving sulfate resistance, reducing leaching and efflorescence, and decreasing both chloride penetration (Mindess et al. 2003) and the formation of calcium oxychloride (Jain et al. 2012, Suraneni et al. 2016, Ghazy and Bassuoni 2017). As explained in Chapters 1 and 2, the formation calcium oxychloride ($CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$) results from a reaction between calcium chloride ($CaCl_2$), due to the application of the deicing salts calcium chloride and magnesium chloride, and calcium hydroxide $Ca(OH)_2$ from during the hydration of portland cement. It is of special concern because it causes severe deterioration; it is both expansive and undergoes phase changes with changes in temperature. The effects of SCMs on scaling, however, are not well understood.

In the laboratory, concrete mixtures incorporating SCMs tend to exhibit more scaling than concrete mixtures containing 100% portland cement (Bouzoubaâ et al. 2011, Hooton and Vassilev 2012), with increasing quantities of SCM generally resulting in greater scaling. The study by Bouzoubaâ et al. (2011) involved mixtures with cement replacements of portland cement with 2% silica fume, 25% Class F fly ash, or 20% Class F fly ash plus 5% silica fume by mass exposed to a 3% sodium chloride (NaCl) solution. These concrete mixtures exhibited mass losses of, respectively, 0.01 lb/ft^2, 0.09 lb/ft^2, and 0.31 lb/ft^2, respectively. The study by Hooton and Vassilev

(2012) included 16 mixtures with both low and high alkali cements and either Grade 100 or 120 slag cement as 0%, 20%, 35%, and 50% replacements by mass of portland cement. They performed three scaling tests: One in accordance with ASTM C672 with 4% $CaCl_2$ and two following a modified version of BNQ 2621-900 with 3% NaCl and two different curing regimes. The modified BNQ 2621-900 used 50 cycles of freezing and thawing, instead of the usual 56 cycles, and evaluated mass loss after 5, 10, 15, 25, and 50 cycles. Across all test methods, increasing SCM replacements tended to result in increased mass loss; their work showed, for example, that the mass losses for concrete mixtures with 100% portland cement, 20% slag cement, 35% slag cement, and 50% slag cement were 0.02 lb/ft^2, 0.20 lb/ft^2, 0.20 lb/ft^2, and 0.55 lb/ft^2, respectively.

In contrast to the laboratory tests, in the field, concrete mixtures containing even high replacement percentages of SCMs have shown have performed well in some cases, but the results have been variable. Schlorholtz and Hooton (2008) investigated the scaling resistance of concrete mixtures incorporating SCMs as 25 to 50% weight replacements of portland cement in bridge decks and pavements with ages ranging from 3 to 17 years. Pavements incorporating 25% slag cement (age 3 years), 35% slag cement and 15% Class C fly ash (ages 5 and 9 years), and 50% slag cement (age 15 years), and bridge decks incorporating 30% slag cement (ages 6 and 7 years), exhibited no damage, while pavements incorporating 35% slag cement (age 6 years), 25% slag cement and 10-15% fly ash (age 17 years), and bridge decks incorporating 20% slag cement and 6% silica fume (ages 4 and 6 years), 20% slag cement and 5% silica fume (age 3 years), and 35% slag cement and 15% Class C fly ash (age 5 years) showed some scaling or other surface damage. There were indications that some of the damage may have been due to poor construction practices. This scatter in behavior indicates that there is a significant need to investigate the effects of using supplementary cementitious materials (SCMs) as partial replacements of portland cement and establish a recommended range replacement percentages of SCMs for bridge decks and pavements. In this study, the use of slag cement and Class C fly ash is evaluated in detail.

In addition to establishing recommended replacement percentages of SCMs, the current study continues prior work at the University of Kansas (KU) aimed primarily at establishing material and construction specifications for low-cracking high-performance concrete (LC-HPC) bridge decks (Lindquist, Darwin, and Browning 2008, McLeod, Darwin, and Browning 2009, Yuan, Darwin, and Browning 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018).

Some of the discrepancies between laboratory and field results may be a function of the laboratory procedures used to evaluate concrete durability. Bouzoubaâ et al. (2008) compared results from laboratory tests (ASTM C672 and BNQ 2621-900) with the performance of concrete in the field. That study showed that results from BNQ 2621-900 more closely matched the scaling resistance of concrete in the field than results from ASTM C672. For this reason, the BNQ 2621-900 test was used in the current study.

This chapter addresses the effects of replacement percentage of SCMs, deicing salt type, curing period, and water-cementitious material (*w/cm*) ratio on the scaling resistance of concrete. The effect of the replacement percentage of SCMs on the scaling resistance of concrete has shown conflicting results in prior studies. Furthermore, previous studies have focused more on Class F fly ash than Class C fly ash. Therefore, in this study, different replacement percentages of Class C fly ash are used as replacements of portland cement. The type of deicing salt is of interest because previous investigations have not studied the effect of deicing salt type on concrete specimens finished, cured, and tested using similar procedures. Thus, comparisons are difficult. The curing period is of interest because it is theorized by some that increased curing is needed for mixtures containing SCMs to provide adequate time for the hydration reactions to occur. Houehanou, Gagné, and Jolin (2010) found that extending the curing period reduced scaling losses. Other studies, however, have found conflicting results with those of Houehanou et al. (2010) on the effect of extending the curing period on the scaling resistance of concrete incorporating SCMs. Bilodeau, Carette, and Malhotra (1991), Talbot at al. (1996), and Bilodeau at al. (1998) found that extending the curing period did not ensure a reduction in scaling and in some cases resulted in an increase. Finally, prior studies have found that reducing the *w/cm* ratio improved the scaling resistance of concrete (Mindess et al. 2003, Hooton and Vassilev 2012). Because previous studies have focused more on Class F fly ash than Class C fly ash, there is a need to better understand the effect of *w/cm* ratio on the scaling resistance of concrete mixtures including SCMs, especially for Class C fly ash.

3.2 RESEARCH SIGNIFICANCE

Due to the increased use of SCMs as partial replacements of portland cement, especially to reduce the effects of calcium oxychloride formation, the impact of deicing salts on scaling of concrete containing SCMs has been a significant concern for several years. Although there have been investigations of the scaling resistance of concrete incorporating SCMs, a number of questions remain unanswered. This study focuses on the effects of replacement percentages of SCMs (20%, 35%, and 50% of slag cement or Class C fly ash) for portland cement, deicing salt type (NaCl or $CaCl_2$), curing period (14 or 28 days), and *w/cm* ratio (0.38 or 0.44).

3.3 EXPERIMENTAL WORK

3.3.1 Materials

Portland cement Type I/II was used in all mixtures. In some mixtures, Class C fly ash or Grade 100 slag cement was used as a partial replacement of portland cement, with replacement described in terms of volume. The water-to-cementitious material ratio (*w/cm*) was based on weight (mass), while the paste content was kept constant at 25% based on an assumed air content of 8% to avoid increasing the paste volume when SCMs were used. Table 3.1 summarizes the chemical compositions of cementitious materials.

Crushed granite was used as the coarse aggregate. To achieve an optimized gradation, the granite was separated into two size fractions, A and B, with maximum sizes of ¾ and ½ in. (19 and 13 mm), respectively. Type A granite had an absorption (dry) of 0.71% and a specific gravity (saturated-surface dry, SSD) of 2.61. Type B granite had an absorption (dry) of 0.87% and a specific gravity (SSD) of 2.60. Pea-gravel and Kansas River sand were used as the fine aggregates. The absorptions (dry) for the pea-gravel and Kansas River sand were 1.3% and 0.42%, respectively, and the specific gravities (SSD) were 2.60 and 2.61, respectively. In this study, an air-entraining admixture (AEA, Euclid AEA-92S) and a high-range water-reducer (HRWR, Euclid Plastol 6400) were used.

Table 3.1: Chemical composition (percentage) and specific gravity of cementitious materials

Component	Portland cement	Class C fly ash	Grade 100 slag cement
SiO_2	20.82	34.99	34.92
Al_2O_3	4.18	17.06	7.64
Fe_2O3	3.11	5.33	0.69
CaO	62.84	30.41	40.94
MgO	2.08	4.54	10.25
SO_3	2.56	1.87	2.72
Na_2O	0.22	1.47	0.3
K_2O	0.56	0.55	0.55
TiO_2	0.25	1.33	0.37
P_2O_5	0.08	0.79	0.01
Mn_2O_3	0.10	0.04	0.53
SrO	0.24	0.31	0.05
Cl^-	0.01	-	0.05
BaO	-	0.35	0.02
LOI	2.96	0.65	0.97
Total	99.99	99.68	100.01
Specific Gravity	3.14	2.63	2.89

3.3.2 Concrete Mixtures

Ten concrete mixtures were cast to study how the replacement percentage of SCMs, deicing salt type, curing period, and water-to-cementitious material ratio (*w/cm*) affect the scaling resistance of concrete. The concrete was cured in lime-saturated water for 14 or 28 days; the salts were sodium chloride (NaCl) or calcium chloride ($CaCl_2$) in solutions with the same molal ion concentration (1.06), equivalent to that of a 3% mass concentration of sodium chloride; the *w/cm* ratios were 0.38 or 0.44, and the SCMs evaluated were slag cement or Class C fly ash. The SCMs had replacement percentages ranging from 20% to 50% by volume of portland cement, and to ensure homogeneity, the SCMs were thoroughly combined with the dry cement prior to mixing. Mixture proportions are listed in Table 3.2. The designations of concrete mixtures are shown in Table 3.2, where the control concrete mixtures incorporated 100% portland cement. For the other concrete mixtures, 20%, 35%, or 50% represents the volume replacement percentage by either slag cement (SL) or fly ash (FA) of portland cement. The values 0.38 or 0.44 represent the *w/cm* ratio of the concrete mixtures.

Table 3.2: Mixture proportions (lb/yd^3)

Mixtures	*w/cm*	Cement	Class C fly ash	Grade 100 slag cement	Water	Sand	Pea gravel	Coarse aggregate		AEA⁺ (fl oz/yd^3)	HRWR* (fl oz/yd^3)
								A	B		
Control-0.44	0.44	556	0	0	245	1099	405	620	816	5.7	0
20% SL-0.44	0.44	452	0	100	243	1095	407	621	818	5.9	0
35% SL-0.44	0.44	369	0	180	242	1090	408	621	819	6.9	0
50% SL-0.44	0.44	286	0	260	240	1087	409	621	821	7.8	0
20% FA-0.44	0.44	454	95	0	242	1090	408	621	819	5.9	0
35% FA-0.44	0.44	374	168	0	238	1101	407	626	843	7.3	0
50% FA-0.44	0.44	292	244	0	236	1092	417	630	834	8.2	0
Control-0.38	0.38	604	0	0	230	1067	418	626	830	3.0	16
20% SL-0.38	0.38	491	0	108	228	1063	420	626	831	3.9	16
20% FA-0.38	0.38	488	107	0	226	1059	422	628	833	3.9	16

+ Air-entraining admixture
* High range water reducing admixture

Table 3.3 summarizes the properties of the concrete. Two batches were cast for each concrete mixture, except one mixture, designated "50% FA-RE-0.44," which had three batches. Batches with the same designations were cast on the same day and under the same laboratory conditions.

Table 3.3: Concrete properties

Mixtures	*w/cm*	Batch	Air Content, %	Slump, in.	Temp., °F	Unit Wt., lb/ft^3	28-day Compressive Strength, psi
Control-0.44	0.44	A	7.75	4	70	140.7	4560
	0.44	B	7.25	4½	69	141.0	4700
Control-RE-0.44	0.44	A	8.00	4½	68	140.6	4880
	0.44	B	7.25	4¾	68	141.0	4850
20% SL-0.44	0.44	A	7.25	3½	68	142.3	4600
	0.44	B	7.75	4	69	141.8	4590
35% SL-0.44	0.44	A	8.00	4½	68	139.5	4780
	0.44	B	8.00	4¼	67	139.3	4480
50% SL-0.44	0.44	A	7.50	3½	70	141.4	5090
	0.44	B	7.75	3¾	70	141.0	5080
50% SL-RE-0.44	0.44	A	7.75	4	68	141.1	4980
	0.44	B	7.50	4¼	68	141.4	5020
20% FA-0.44	0.44	A	8.00	4¾	68	141.2	4470
	0.44	B	7.50	5	68	142.3	4640
35% FA-0.44	0.44	A	7.25	7	69	141.4	4560
	0.44	B	7.50	7	70	141.8	4870
50% FA-0.44	0.44	A	7.25	7½	67	142.3	4210
	0.44	B	7.25	7½	68	142.7	4260
50% FA-RE-0.44	0.44	A	7.75	7¾	69	141.4	4280
	0.44	B	7.75	8	70	141.9	4250
	0.44	C	7.50	8	69	142.2	4300
Control-0.38	0.38	A	8.00	3	68	142.9	5860
	0.38	B	7.50	2¾	67	143.4	5760
20% SL-0.38	0.38	A	7.75	3	70	141.9	5990
	0.38	B	7.50	3¼	69	143.0	5820
20% FA-0.38	0.38	A	7.75	4¾	69	142.7	5630
	0.38	B	8.00	5¼	68	143.0	5600

3.3.3 Test Procedures

The scaling test was performed in accordance with Quebec Test BNQ NQ 2621-900 Annex B, with minor modifications to the temperature range for the freeze-thaw cycle. BNQ NQ 2621-900 uses a temperature of -0.4 ± 5.4 ºF (-18 ± 3 ºC) for the freezing period followed by a temperature of 77 ± 5.4 ºF (25 ± 3 ºC) for the thawing period. The procedure specifies no limits on relative humidity (RH). In this study, the temperature was 0 ± 5 ºF (-18 ± 3 ºC) during the freezing period and 73 ± 3 ºF (23 ± 2 ºC) during the thawing period. During the thawing period, the RH was 50% ± 4%.

Six 9 × 16 × 3 in. (229 × 406 × 76 mm) specimens were cast for each batch using wooden molds. The concrete was mixed, and the specimens were fabricated in accordance with ASTM C192. The concrete was placed in the molds in two equal layers, and each layer was consolidated on a vibrating table with an amplitude of 0.006 in. (0.1 mm) and a frequency of 60 Hz for 15 to 30 seconds. The upper surface of the specimens was struck off with a 3 × ¾ in. (76 × 19 mm) wooden screed. After strike off, 6-mil (152-µm) plastic sheets with approximate dimensions of 10 × 17 in. were placed on the upper surface of the concrete specimens, and to prevent evaporation, a 3.5-mil (89-µm) plastic sheet was used to cover the top and sides of the specimen and secured with rubber bands. A ½ in. thick piece of plexiglass and an old scaling specimen, which weighed approximately 35 lb, was placed on the top of the specimens. After 24 hours, the specimens were demolded and cured in lime-saturated water. From each batch, three specimens were cured for 14 days, and three specimens were cured for 28 days. After curing, the specimens were dried in an environmentally-controlled room at 73 ± 3 ºF (23 ± 2 ºC) and a relative humidity of 50 percent ± 4 percent for 14 days. On the sixth day of drying, a polyurethane sealant was used to attach an expanded polystyrene dike to the finished surface of the specimen, as shown in Figure 3.1. At the end of the drying period, a ¼ in. (6 mm) deep layer of either NaCl or $CaCl_2$ solution was poured within the dike to pre-saturate the specimens. The specimens were covered with plastic sheets to prevent evaporation of the solutions and were stored for 7 days in the environmentally-controlled room.

Figure 3.1: Scaling resistance test specimen

After the pre-saturation period, the specimens were exposed to cycles of freezing and thawing. Each cycle included a 16 ± 1 hour freezing phase followed by an 8 ± 1 hour thawing phase. Mass loss in the specimens was measured after 7, 21, 35, and 56 cycles. To measure mass loss, the loose materials on the surface of the specimens were wet sieved over a No. 200 (75 µm) sieve. The material retained on the No. 200 sieve was dried for approximately 24 hours at 212 ºF (100 ºC). The total mass of material (including cumulative material lost from prior cycles) is then divided by the average surface area of the inside of the specimen to calculate the cumulative mass loss in terms of lb/ft^2 (1 lb/ft^2 = 4882 g/m^2). New salt solution was then added to specimens prior to returning them to testing. The maximum allowable average cumulative mass losses at the end of the test are 0.10 lb/ft^2 (500 g/m^2) and 0.16 lb/ft^2 (800 g/m^2) in accordance with Quebec Test BNQ NQ 2621-900 and the Ministry of Transportation of Ontario (MTO), respectively.

The test differs from ASTM C672, which uses a 4% $CaCl_2$ solution, does not require a pre-saturation period, and includes 50 rather than 56 freeze-thaw cycles. ASTM C672 uses a 16 to 18 hour freezing period at 0 ± 5 ºF (-18 ± 3 ºC) and a 6 to 8 hour thawing period at 73.5 ± 3.5 ºF (23 ± 2 ºC) with RH of 45% to 55%.

3.4 EXPERIMENTAL RESULTS AND DISCUSSION

The scaling test results are presented in Table 3.4 and Figures 3.2 to 3.15. Table 3.4 shows the average cumulative mass loss at 56 cycles. To evaluate the effects of the test parameters on scaling, Student's t-test is used to examine the statistical significance of differences in scaling as a function of replacement percentage of SCMs, deicing salt type, curing period, and *w/cm* ratio. In this study, if the *p*-value (the probability that the observed difference in means is due to random variation rather than a meaningful difference in behavior) is less than or equal to 0.05, the difference between results is considered to be statistically significant.

Table 3.4: Average cumulative mass loss at 56 cycles (lb/ft^2)

	Type of salt – Curing period			
Concrete mixture	NaCl - 14 days of curing	NaCl - 28 days of curing	$CaCl_2$ - 14 days of curing	$CaCl_2$ - 28 days of curing
Control–0.38	0.01	0.01	0.02	0.02
20% SL–0.38	0.02	0.03	0.04	0.04
20% FA–0.38	0.02	0.02	0.02	0.02
Control–0.44	0.02	0.02	0.04	0.04
Control–0.44–RE	0.02	0.02	0.04	0.05
20% SL–0.44	0.03	0.04	0.05	0.04
20% FA–0.44	0.03	0.03	0.03	0.02
35% SL–0.44	0.06	0.07	0.03	0.03
50% SL–0.44	0.20	0.18	0.09	0.08
50% SL–0.44–RE	0.19	0.16	0.11	0.10
35% FA–0.44	0.05	0.05	0.03	0.04
50% FA–0.44	0.15	0.27	0.06	0.08
50% FA–0.44–RE	0.15	0.20	0.05	0.07

3.4.1 Effects of Replacement Percentage of SCMs, Deicing Salt Type, and Curing Period on Scaling Resistance

This section describes the effect of the replacement percentage of slag cement or Class C fly ash on the scaling resistance of concrete. The effects of deicing salt type (NaCl or $CaCl_2$) and the curing period (14 days or 28 days) on the scaling resistance of concrete are also presented.

3.4.1.1 Effect of Replacement Percentage of SCMs on Scaling

Figures 3.2 to 3.5 show the effects of 20%, 35%, and 50% replacements by volume of portland cement with slag cement or Class C fly ash on the mass loss of concrete mixtures. Table C2 in Appendix C shows the results of Student's t-test.

Figure 3.2 shows the average cumulative mass loss for mixtures cured for 14 days and exposed to NaCl. These results indicate that incorporating slag cement or Class C fly ash generally causes an increase in scaling compared to that observed for mixtures with 100% portland cement. Mixtures with 100% portland cement exhibited mass losses of 0.01 to 0.02 lb/ft^2. Mixtures with 20% replacements with slag cement or Class C fly ash had mass losses of 0.02 to 0.03 lb/ft^2, with no notable difference between slag cement and Class C fly ash. Increasing the replacement of either SCM to 35% increased the mass loss, with values of 0.06 lb/ft^2 for slag cement and 0.05 lb/ft^2 for Class C fly ash. All of these values are below the BNQ failure limit of 0.10 lb/ft^2.

Using a 50% SCM volume replacement, however, resulted in a notable increase in mass loss, with values of 0.19 and 0.20 lb/ft^2 for slag cement and 0.15 lb/ft^2 for Class C fly ash – exceeding the BNQ NQ 2621-900 failure limit of 0.10 lb/ft^2 (500 g/m^2) and MTO failure limit of 0.16 lb/ft^2 (800 g/m^2) and representing significantly poorer performance than that of the mixtures with 100% portland cement or 20% or 35% SCM replacements. The differences in the mass loss between the mixtures with 50% cement replacements with SCMs and those with 100% portland cement, 20% or 35% SCMs are statistically significant ($p = 6.18\times10^{-6}$ to 1.45×10^{-3}).

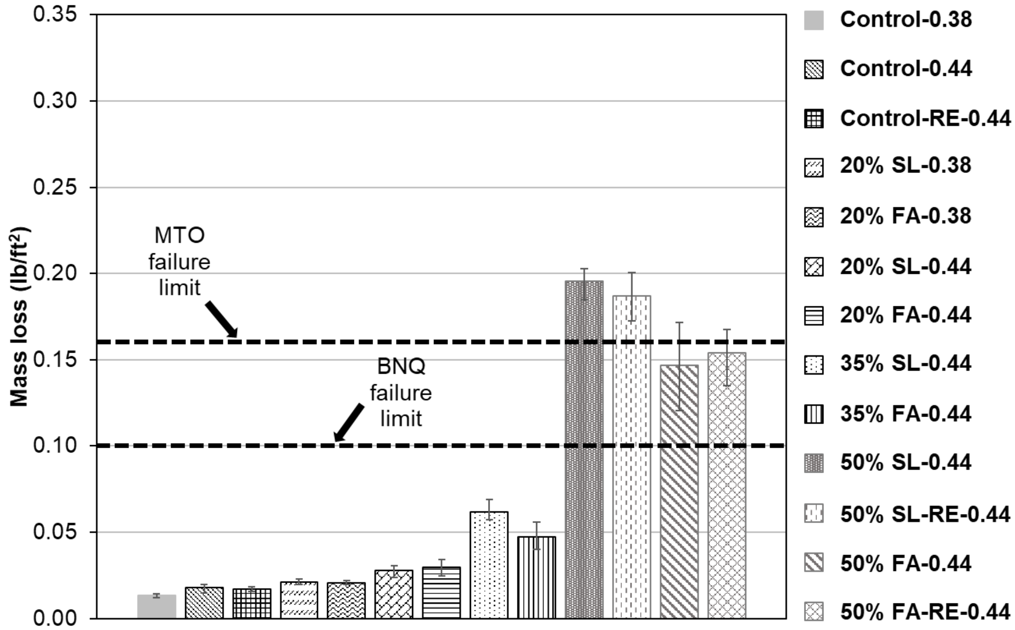

Figure 3.2: Average cumulative mass loss of concrete mixtures with 100% portland cement, 20%, 35%, 50% slag cement or Class C fly ash cured for 14 days and exposed to NaCl

Figure 3.3 shows the average cumulative mass loss of concrete mixtures cured for 14 days and exposed to $CaCl_2$. These results indicate that incorporating 20% or 35% of slag cement or 20%, 35%, or 50% Class C fly ash resulted in a slight increase in mass loss compared to the mass loss of mixtures with 100% portland cement, while replacing 50% of portland cement with slag cement resulted in a noticeable increase in mass loss. Mixtures with 100% portland cement exhibited mass losses of 0.02 to 0.04 lb/ft^2. A 20% replacement with slag cement or Class C fly ash resulted in mass losses of 0.02 to 0.05 lb/ft^2, with mixtures containing slag cement having higher values of mass loss. The concrete mixture with 35% slag cement had a mass loss of 0.03 lb/ft^2 compared to the concrete mixture with 20% slag cement, which had a mass loss of 0.04 lb/ft^2. The mixtures with 20% and 35% Class C fly ash had the same mass loss, 0.03 lb/ft^2.

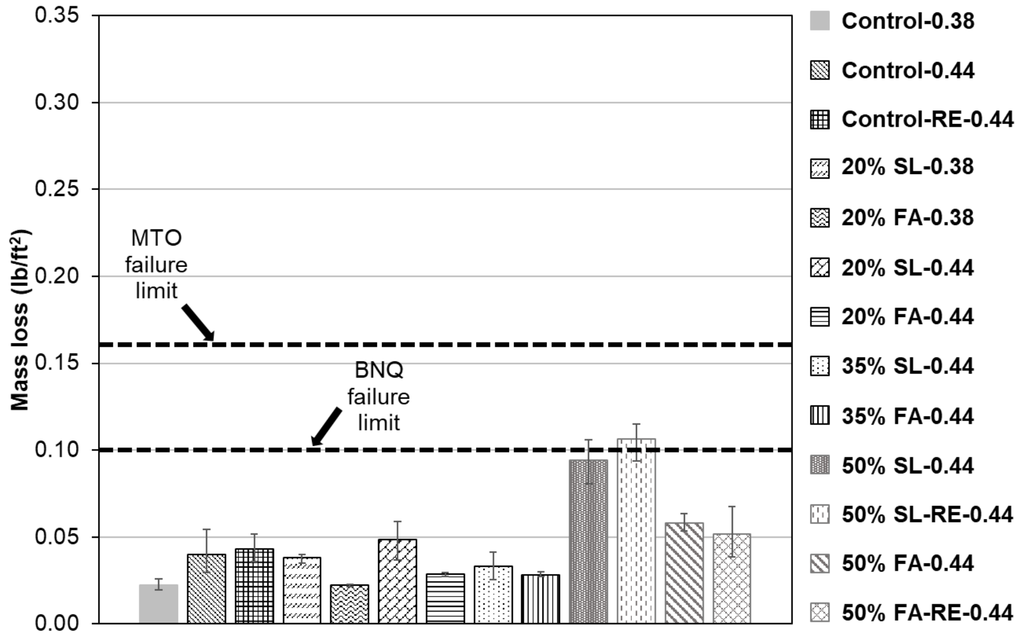

Figure 3.3: Average cumulative mass loss of concrete mixtures with 100% portland cement, 20%, 35%, 50% slag cement or Class C fly ash cured for 14 days and exposed to $CaCl_2$

A notable increase in mass loss compared to that of mixtures with 100% portland cement, 20% slag cement or 35% slag cement is observed for mixtures with 50% slag cement. These differences are statistically significant ($p = 8.09\times10^{-4}$ and 6.81×10^{-3}). The mass losses of 0.09 and 0.11 lb/ft^2 for the two batches of concrete containing 50% slag cement are, respectively, just below and just above the BNQ NQ 2621-900 failure limit but below the MTO failure limit. The mass losses for mixtures containing 50% Class C fly ash, 0.05 and 0.06 lb/ft^2, are slightly greater than the mass losses of mixtures with 100% portland cement and 20% or 35% Class C fly ash, differences that are not statistically significant; these values are below the failure limits of both BNQ NQ 2621-900 and MTO.

The mass losses for the mixtures with 50% SCMs cured for 14 days shown in Figures 3.2 and 3.3 indicate that exposure to NaCl causes 75% to 153% more mass loss than exposure to $CaCl_2$. The effect of deicing salt type is discussed at greater length in Section 3.4.1.2.

Figure 3.4 shows the average cumulative mass loss of concrete mixtures cured for 28 days and exposed to NaCl. These results again show that incorporating slag cement or Class C fly ash causes an increase in mass loss compared to mixtures with 100% portland cement. Mixtures with 100% portland cement exhibited mass losses of 0.01 to 0.02 lb/ft^2. Mixtures with 20% slag cement or Class C fly ash replacements of portland cement had mass losses of 0.02 to 0.04 lb/ft^2, with the mixtures containing slag cement having slightly higher losses. Increasing the SCM replacement to 35% caused an increased mass loss, with values of 0.07 lb/ft^2 for slag cement and 0.05 lb/ft^2 for Class C fly ash. As for the mixtures that were cured for 14 days, using a 50% replacement of portland cement with slag cement or Class C fly ash resulted in a notable increase in mass loss, with the mixtures containing Class C fly ash having the higher losses; the mass losses of 0.16 and 0.18 lb/ft^2 for the mixtures containing 50% slag cement and 0.20 and 0.27 lb/ft^2 for the mixtures containing 50% Class C fly ash exceed the failure limits for both BNQ NQ 2621-900 and MTO. The differences in the mass loss for mixtures with 50% slag cement or Class C fly ash with those of mixtures with 100% portland cement, 20%, 35% slag cement or Class C fly ash are statistically significant ($p = 2.62\times10^{-7}$ to 1.31×10^{-3}).

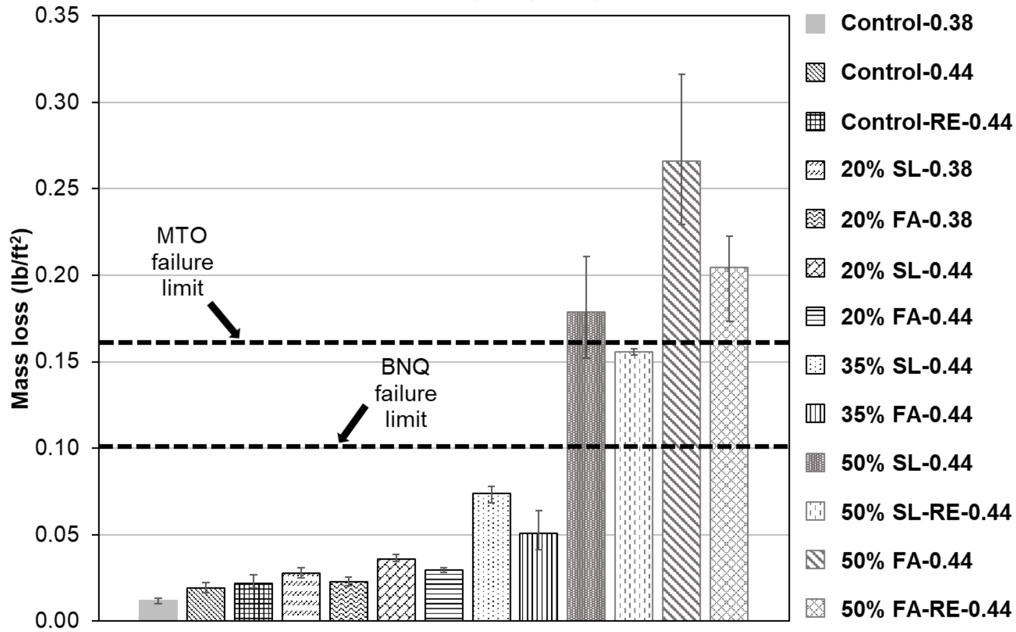

Figure 3.4: Average cumulative mass loss of concrete mixtures with 100% portland cement, 20%, 35%, 50% slag cement or Class C fly ash cured for 28 days and exposed to NaCl

Figure 3.5 shows the average cumulative mass loss of concrete mixtures cured for 28 days and exposed to $CaCl_2$. All mixtures had losses below the BNQ NQ 2621-900 failure limit of 0.10 lb/ft^2. These results indicate that incorporating 20% or 35% of slag cement or Class C fly ash resulted in generally similar mass losses to those of the mixtures with 100% portland cement. As observed for the mixtures cured for 14 days and exposed to NaCl, replacing 50% of the portland cement with slag cement or Class C fly ash resulted in a noticeable increase in mass loss. Mixtures with 100% portland cement had mass losses of 0.02 to 0.05 lb/ft^2. Mixtures with a 20% replacement with slag cement or Class C fly ash had mass losses of 0.02 to 0.04 lb/ft^2, and mixtures with 35% replacements with slag cement and Class C fly ash had mass losses of 0.03 lb/ft^2 and 0.04 lb/ft^2, respectively. Although the losses were at or below the BNQ NQ 2621-900 failure limit, the mixtures with a 50% SCM replacement exhibited a noticeable increase in mass loss with values of 0.08 and 0.10 lb/ft^2 for slag cement and 0.07 and 0.08 lb/ft^2 for Class C fly ash. The differences in mass loss between the mixtures with 50% slag cement and those with 100% portland cement, 20% or 35% slag cement are statistically significant ($p = 3.78\times10^{-5}$ to 1.87×10^{-2}). The differences in mass loss between mixtures with 50% Class C fly ash and those with 20% Class C fly ash are statistically significant ($p = 1.14\times10^{-3}$ to 2.33×10^{-2}) while the differences between mixtures with 50% Class C fly ash and those containing 100% portland cement, and 35% Class C fly ash are not.

The mass losses for mixtures with 50% SCMs and cured for 28 days show that exposure to NaCl resulted in 55% to 217% more mass loss than exposure to $CaCl_2$. (See Section 3.4.1.2).

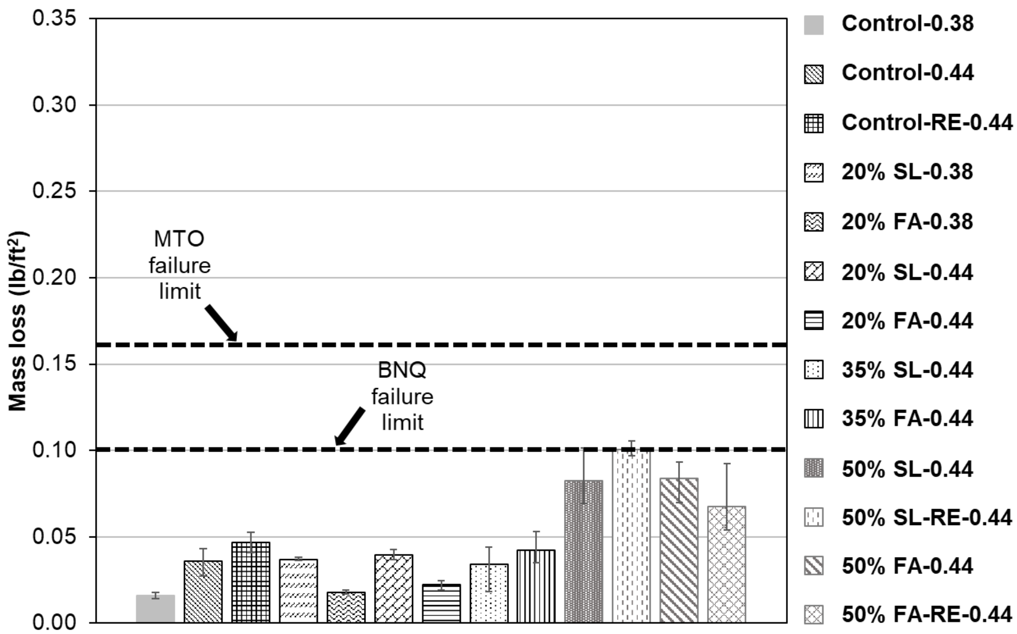

Figure 3.5: Average cumulative mass loss of concrete mixtures with 100% portland cement, 20%, 35%, 50% slag cement or Class C fly ash cured for 28 days and exposed to $CaCl_2$

Figures 3.6 and 3.7 compare the average cumulative mass losses for concrete mixtures with slag cement versus those incorporating Class C fly ash when exposed to NaCl and $CaCl_2$, respectively. In the legend, 0.38 and 0.44 represent the *w/cm* ratios; hollow markers represent specimens with 14 days of curing and shaded markers represent specimens with 28 days of curing. The dashed line represents the case of equal mass loss for mixtures incorporating slag cement or Class C fly ash.

Figure 3.6 shows that in most cases, mixtures incorporating slag cement and Class C fly ash exhibited similar mass losses, with those incorporating slag cement showing somewhat greater losses a replacement levels of 20% and 35%.

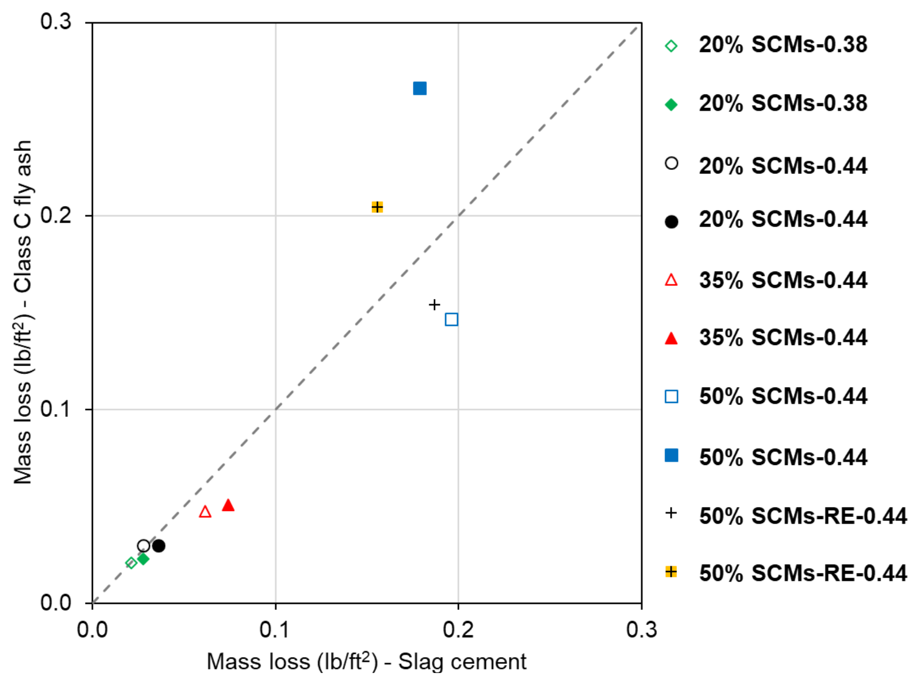

Figure 3.6: Comparison of average cumulative mass losses of concrete mixtures incorporating slag cement with those incorporating Class C fly ash exposed to NaCl. Hollow markers represent specimens with 14 days of curing and shaded markers represent specimens

Figure 3.7 shows that in most cases, mixtures incorporating slag cement had more mass loss than those incorporating Class C fly ash. This difference is likely due to the greater effectiveness of fly ash in reducing the quantity of calcium hydroxide, and thus calcium oxychloride, than slag cement.

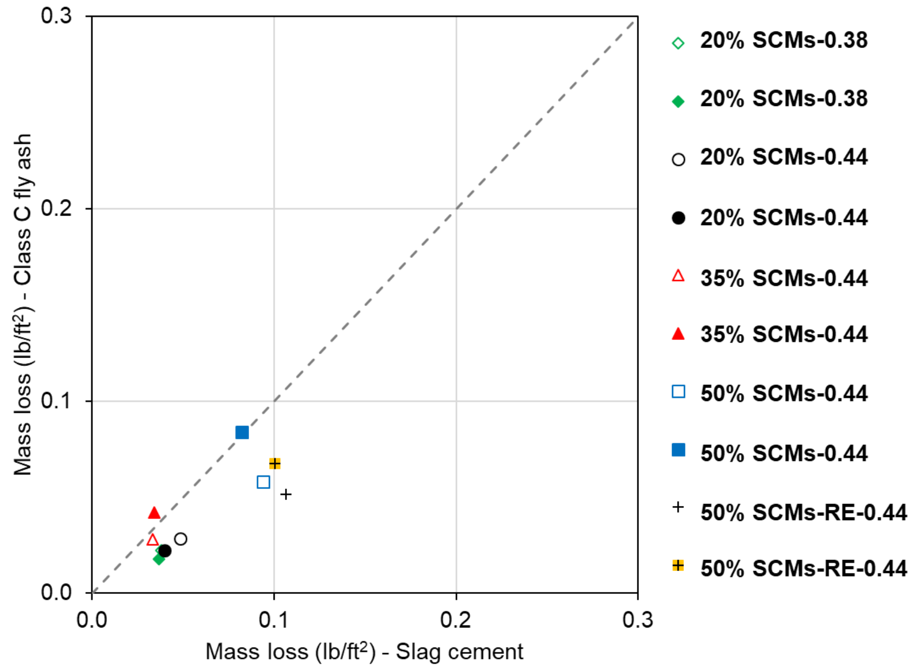

Figure 3.7: Comparison of average cumulative mass losses of concrete mixtures incorporating slag cement with those incorporating Class C fly ash exposed to $CaCl_2$. Hollow markers represent specimens with 14 days of curing and shaded markers represent specimens

In general, using slag cement or Class C fly ash as a replacement of portland cement results in an increase in scaling compared to mixtures with 100% portland cement. The increase in scaling is greater for mixtures exposed to NaCl than to mixtures exposed to $CaCl_2$. In most cases, mixtures incorporating slag cement have more mass loss than those incorporating Class C fly ash. As stated above, regardless of the deicing salt type and the curing period, concrete mixtures incorporating 20% or 35% slag cement or Class C fly ash exhibited mass losses (0.02 to 0.07 lb/ft^2) that were below the 0.10 lb/ft^2 failure limit of BNQ NQ 2621-900 and well below the 0.16 lb/ft^2 failure limit of MTO. Replacing portland cement with 50% slag cement or Class C fly ash, however, results in increased scaling, especially for mixtures exposed to NaCl. These results support a 35% maximum allowable replacement percentage for both slag cement or Class C fly ash for concrete subjected to freezing and thawing and exposure to deicing salts.

3.4.1.2 Effect of Deicing Salt Type on Scaling

In this section, the effect of the deicing salt (NaCl or $CaCl_2$) on mass loss due to scaling is presented. Table C.2 in Appendix C shows results of Student's t-test.

Figures 3.8, 3.9 and 3.10 compare the average cumulative mass losses for control concrete mixtures (100% portland cement), concrete mixtures with slag cement, and concrete mixtures with fly ash, respectively, when exposed to NaCl with those occurring due to exposure to $CaCl_2$. In the legend, 0.38 and 0.44 represent the *w/cm* ratios; hollow markers represent specimens with 14 days of curing and shaded markers represent specimens with 28 days of curing. The dashed line represents the case of equal mass loss for mixtures exposed to NaCl and $CaCl_2$.

Figure 3.8 shows that exposure to $CaCl_2$ resulted in 38% to 151% more scaling than exposure to NaCl for the control mixtures (100% portland cement). These differences are statistically significant ($p = 4.31\times10^{-3}$ to 4.29×10^{-2}). This finding is in line with observations by Hooton and Vassilev (2012) who found that concrete mixtures with 100% portland cement had 4% to 1020% more mass loss when exposed to $CaCl_2$ (4% $CaCl_2$ in accordance with ASTM C672) than when exposed to NaCl (3% NaCl in accordance with the modified BNQ 2621-900). Part of the difference may have been due to differences in specimen preparation, but it seems apparent that the difference in deicing salt played a major role in the observed difference in scaling.

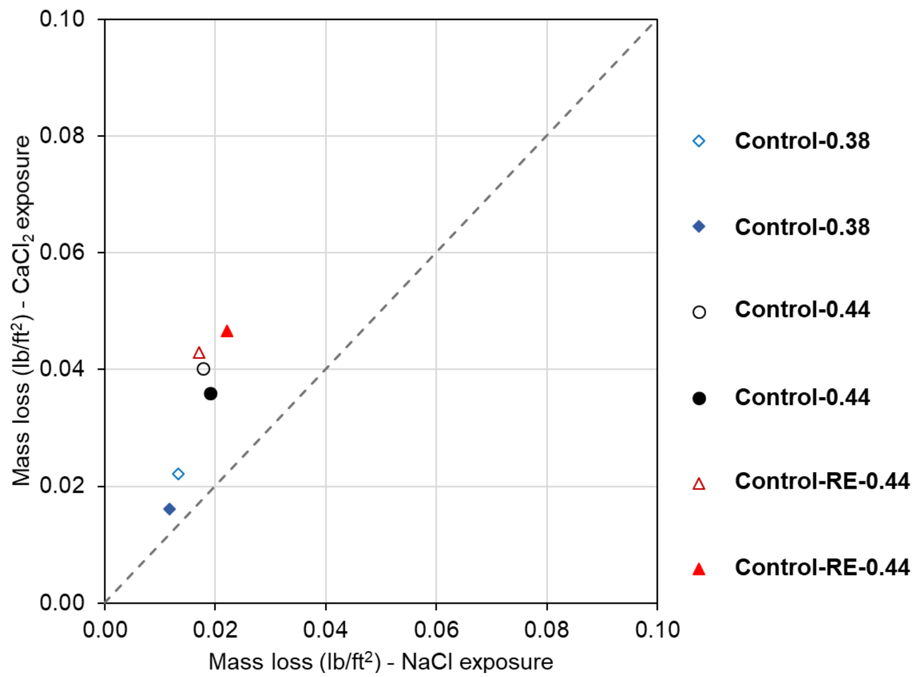

Figure 3.8: Comparison of average cumulative mass losses of control concrete mixtures (100% portland cement) exposed to $CaCl_2$ with those exposed to NaCl. Hollow markers represent specimens with 14 days of curing and shaded markers represent specimens with 28 days of curing

Figure 3.9 shows that exposure to $CaCl_2$ caused 11% to 80% more scaling than NaCl for mixtures incorporating 20% slag cement. These differences are statistically significant, except for the mixture with a *w/cm* ratio of 0.44 and cured for 28 days. Increasing the replacement percentage to 35% or 50% of slag cement, however, resulted in exposure to NaCl causing 55% to 117% more scaling than $CaCl_2$. These differences are statistically significant ($p = 4.12\times10^{-5}$ to 9.21×10^{-3}). This finding is supported by the study of Hooton and Vassilev (2012) who found that most mixtures with 20% slag cement exposed to $CaCl_2$ (4% $CaCl_2$ solution in accordance with ASTM C672) had 159% to 257% more mass loss than when exposed to NaCl (3% NaCl solution in accordance with modified BNQ 2621-900). By increasing the replacement percentage of slag cement to 35% and 50%, Hooton and Vassilev (2012) found, however, that NaCl caused more mass loss than $CaCl_2$. Of four mixtures with 35% slag cement, one had less mass loss, 54%, and three had more mass loss, 6% to 67%, when exposed to NaCl than $CaCl_2$, and all six mixtures with 50% slag cement had more mass loss, 4% to 65%, when exposed to NaCl than $CaCl_2$.

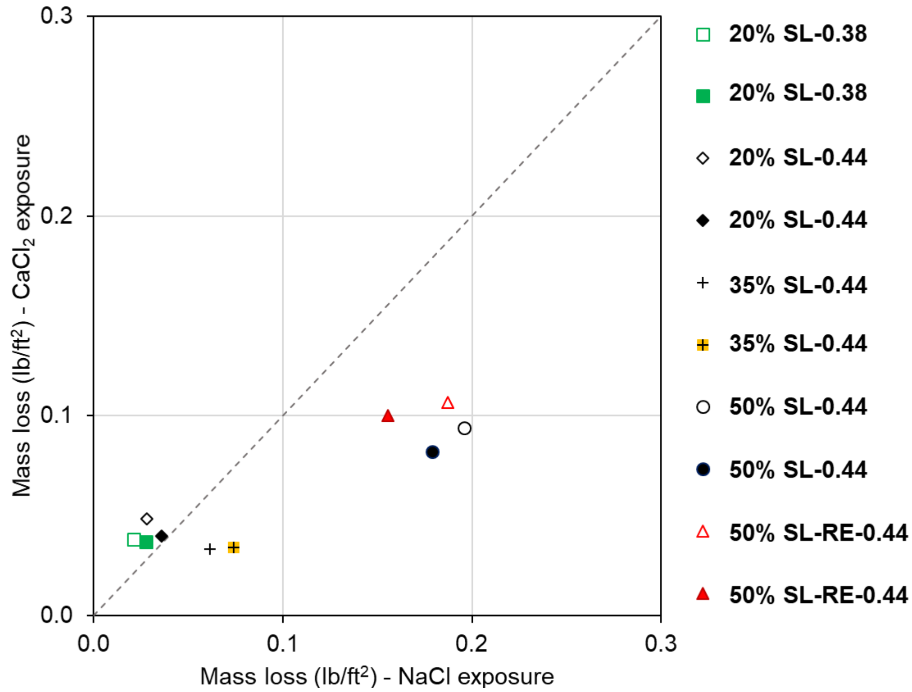

Figure 3.9: Comparison of average cumulative mass losses of concrete mixtures incorporating slag cement (SL) exposed to $CaCl_2$ with those exposed to NaCl. Hollow markers represent specimens with 14 days of curing and shaded markers represent specimens with 28 days of curing

Figure 3.10 shows that exposure to NaCl resulted in progressively greater scaling than $CaCl_2$ for mixtures incorporating Class C fly ash as the fly ash content increased. For 20% and 35% fly ash replacement, specimens had 4% to 68% more mass loss when exposed to NaCl than $CaCl_2$. The differences in mass loss for mixtures with 20% Class C fly ash for both *w/cm* ratios and cured for 28 days, and mixture with 35% Class C fly ash and cured for 14 days are statistically significant (p = 1.37×10^{-2} to 3.39×10^{-2}) while in other cases are not. For a 50% Class C fly ash replacement, exposure to NaCl resulted in 153% to 217% more mass loss than exposure to $CaCl_2$. These differences are statistically significant (p = 1.40×10^{-3} to 4.11×10^{-3}).

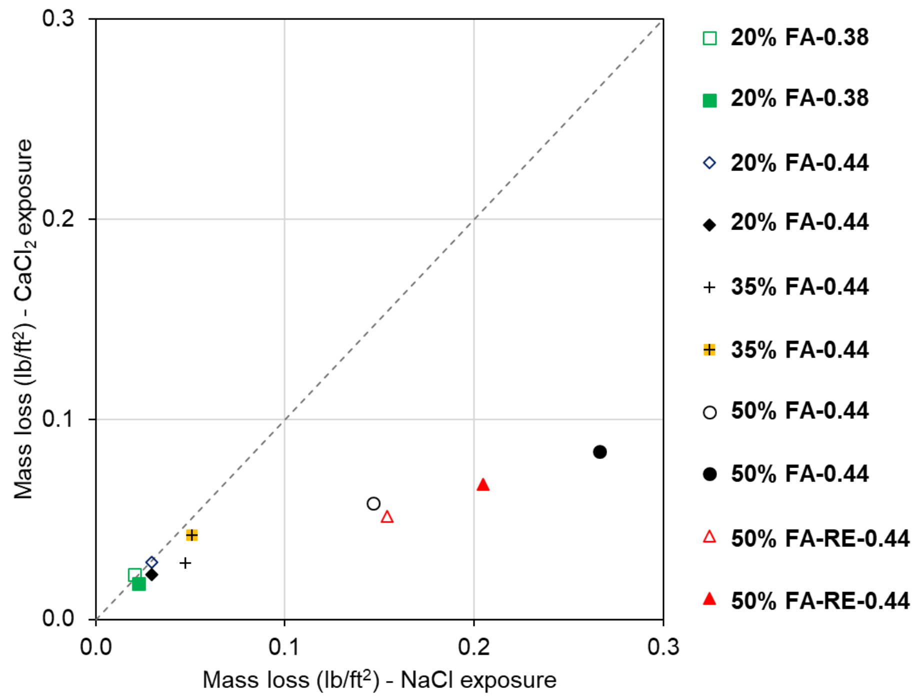

Figure 3.10: Comparison of average cumulative mass losses of concrete mixtures incorporating Class C fly ash (FA) exposed to $CaCl_2$ with those exposed to NaCl. Hollow markers represent specimens with 14 days of curing and shaded markers represent specimens with 28 days of curing

As shown in Figures 3.8 through 3.10, $CaCl_2$ caused more scaling than NaCl for mixtures with 100% portland cement and with 20% slag cement. This increase in scaling is most likely due damage caused by the formation of calcium oxychloride ($CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$). As the SCM replacement percentage increases, however, exposure to $CaCl_2$ becomes less detrimental because slag cement and Class C fly ash cause a reduction in $Ca(OH)_2$, and therefore, less calcium oxychloride. The use of 20% Class C fly ash results in less scaling in the presence of $CaCl_2$ than slag cement, likely because it results in a greater reduction in $Ca(OH)_2$. The use of NaCl, which does not result in the formation of calcium oxychloride, causes more scaling than $CaCl_2$ as the replacement percentage of SCMs increases. Overall, the results show that scaling is a complex phenomenon that is not governed by a single mechanism.

The findings in the current study are in concert with those obtained in a more limited study by Hooton and Vassilev (2012). Hooton and Vassilev (2012) observed that concrete mixtures with 100% portland cement had greater mass loss when exposed to $CaCl_2$ (4% $CaCl_2$ in accordance with ASTM C672) than when exposed to NaCl (3% NaCl in accordance with the modified BNQ 2621-900), but that most concrete mixtures with 35% slag cement replacements and all concrete mixtures with a 50% slag cement replacements exhibited more mass loss when exposed to NaCl.

3.4.1.3 Effect of Curing Period on Scaling Resistance

The mixtures in this study were cured for 14 or 28 days. Figures 3.11, 3.12 and 3.13 compare the effect of curing period on the mass loss of concrete mixtures exposed to NaCl or $CaCl_2$ with *w/cm* ratios of 0.38 or 0.44. In the legend, 0.38 and 0.44 represent the values of *w/cm* ratio; hollow markers represent exposure to NaCl, and shaded markers represent exposure to $CaCl_2$. The horizontal axis depicts the average cumulative mass loss of the mixtures cured for 14 days, and the vertical axis depicts the average cumulative mass loss of the mixtures cured for 28 days. The dashed line indicates that mass loss was equivalent for 14 and 28 days of curing. Table C.2 in Appendix C shows the results of Student's t-test for all comparisons.

Figure 3.11 compares the effect of curing period on the mass loss of the control mixtures (100% portland cement). Extending the curing period resulted in little change in scaling for these mixtures. In no case was the difference in mass loss based on curing period statistically significant. Thus, extending the curing period from 14 to 28 days appears to have no effect on the scaling of concrete with portland cement as the only binder.

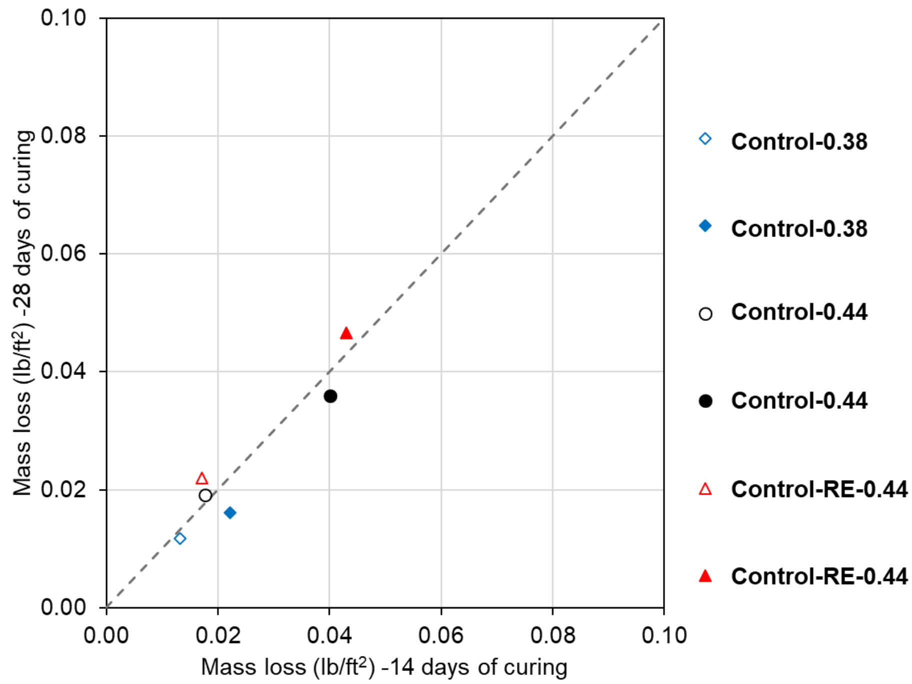

Figure 3.11: Comparison of average cumulative mass losses of control mixtures cured for 14 days with those cured for 28 days. Hollow markers represent exposure to NaCl, and shaded markers represent exposure to $CaCl_2$

Figure 3.12 compares the effect of curing period on the mass loss of concrete mixtures with different replacement percentages of slag cement. Again, as observed for the control (100% portland cement) mixtures, no meaningful differences are observed in mass loss when curing concrete containing slag cement for 14 or 28 days.

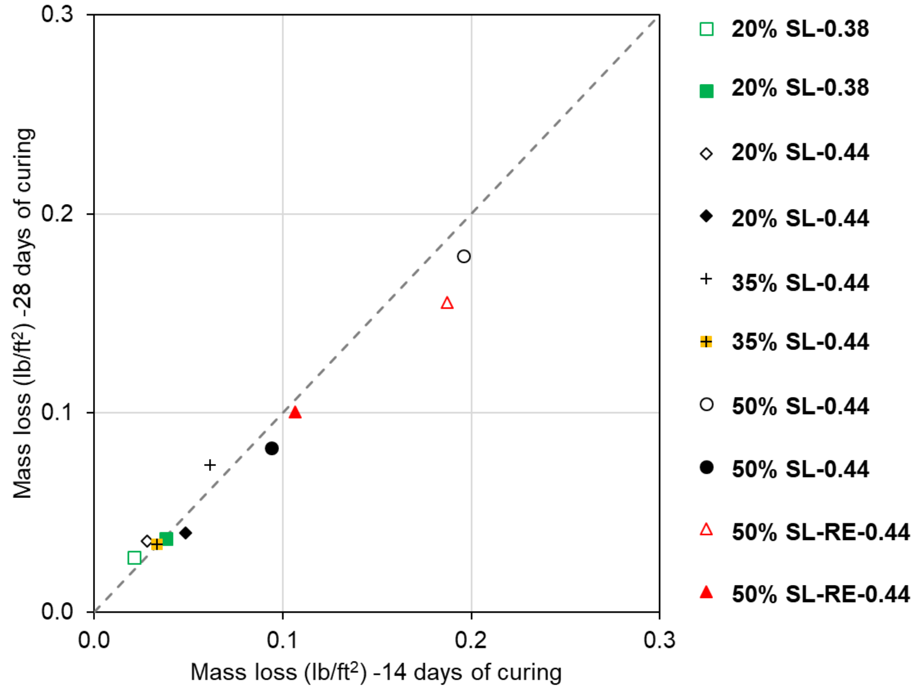

Figure 3.12: Comparison of average cumulative mass losses of mixtures incorporating slag cement (SL) cured for 14 days with those cured for 28 days. Hollow markers represent exposure to NaCl, and shaded markers represent exposure to $CaCl_2$

Figure 3.13 compares the effect of curing period on the mass loss of concrete mixtures with different replacement percentages of Class C fly ash. In this case, increasing the curing time *increased* the mass loss for concrete containing at least 35% Class C fly ash, a difference that is statistically significant for the mixtures with a 50% replacement, but not 35%.

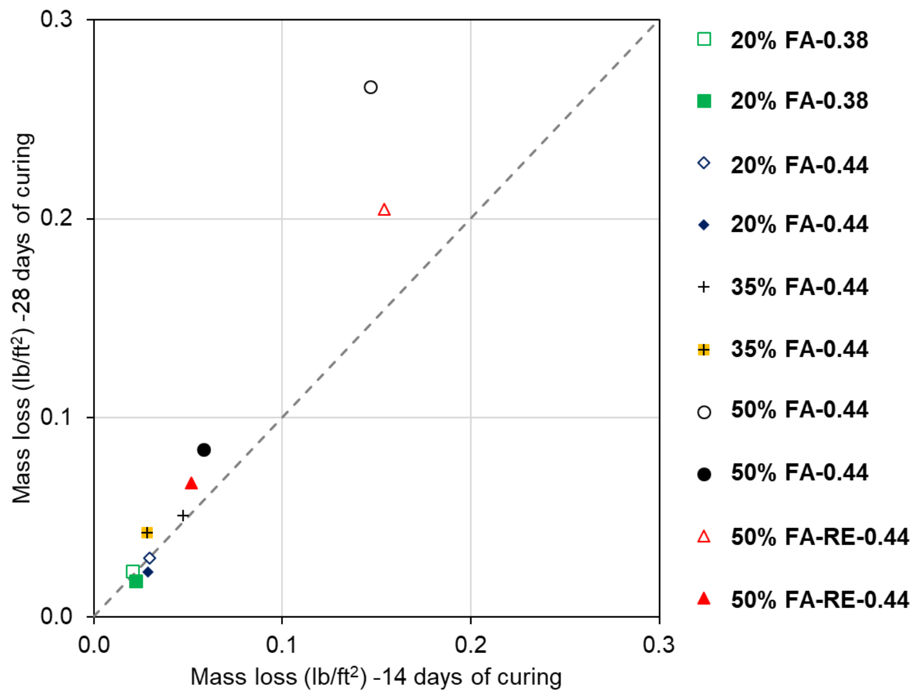

Figure 3.13: Comparison of average cumulative mass losses for mixtures incorporating Class C fly ash (FA) cured for 14 days with those cured for 28 days. Hollow markers represent exposure to NaCl, and shaded markers represent exposure to $CaCl_2$

The results presented in Figure 3.11 through 3.13 show that extending the curing period to 28 days had little effect on scaling for most mixtures in this study. The noticeable exception was the concrete with 50% Class C fly ash for which the mass loss increased for the specimens with the longer curing period. Thus, it can be concluded that extending the curing period from 14 to 28 days will not enhance and may be detrimental to scaling resistance. This finding is in line with investigations by Bilodeau, Carette, and Malhotra (1991) (3, 7, and 14 days of curing in a moist room), Talbot at al. (1996) (14 and 28 days of curing in lime-saturated water), and Bilodeau at al. (1998) (7, 14, 28, and 56 days of curing in a moist room at 73 ºF (23 ºC)) that also found that extending the curing period did not improve scaling resistance and, in some cases, caused an increase in scaling. Houehanou, Gagné, and Jolin (2010), however, found that extending the curing period in a moist room from 14 to 28 days resulted in a reduction in scaling.

3.4.2 Effect of Water-to-Cementitious Materials Ratio on Scaling

The effect of the *w/cm* ratio on the scaling loss of concrete mixtures is presented in this section. Table C3 Appendix C shows the results of Student's t-test.

Figures 3.14 and 3.15 compare the mass loss of concrete mixtures with a *w/cm* ratio of 0.38 with that of mixtures with a *w/cm* ratio of 0.44 for mixtures exposed to NaCl and $CaCl_2$, respectively. In the legend, 0.38 and 0.44 represent the values of *w/cm* ratios; hollow markers represent specimens with 14 days of curing and shaded markers represent specimens with 28 days of curing. The value on the horizontal axis represents the average cumulative mass loss of concrete mixtures with a *w/cm* ratio of 0.44, and the value on the vertical axis represents the average cumulative mass loss of concrete mixture with a *w/cm* ratio of 0.38. The dashed line represents the case of equal mass loss for mixtures with the two *w/cm* ratios.

The figures show that, regardless of the type of deicing salt, reducing the *w/cm* ratio from 0.44 to 0.38 resulted in a reduction (8% to 123%) in mass loss for all concrete mixtures. These differences are, in most cases, statistically significant ($p = 1.03\times10^{-3}$ to 6.14×10^{-2}). The differences are not statistically significant for mixtures with 100% cement cured for 14 days exposed to either NaCl or $CaCl_2$ and for mixtures with 20% slag cement cured for 14 or 28 days exposed to $CaCl_2$. This finding is in line with expectations and with previous studies that found that reducing the *w/cm* ratio improves the scaling resistance of concrete (Pigeon and Pleau 1995, Hooton and Vassilev 2012).

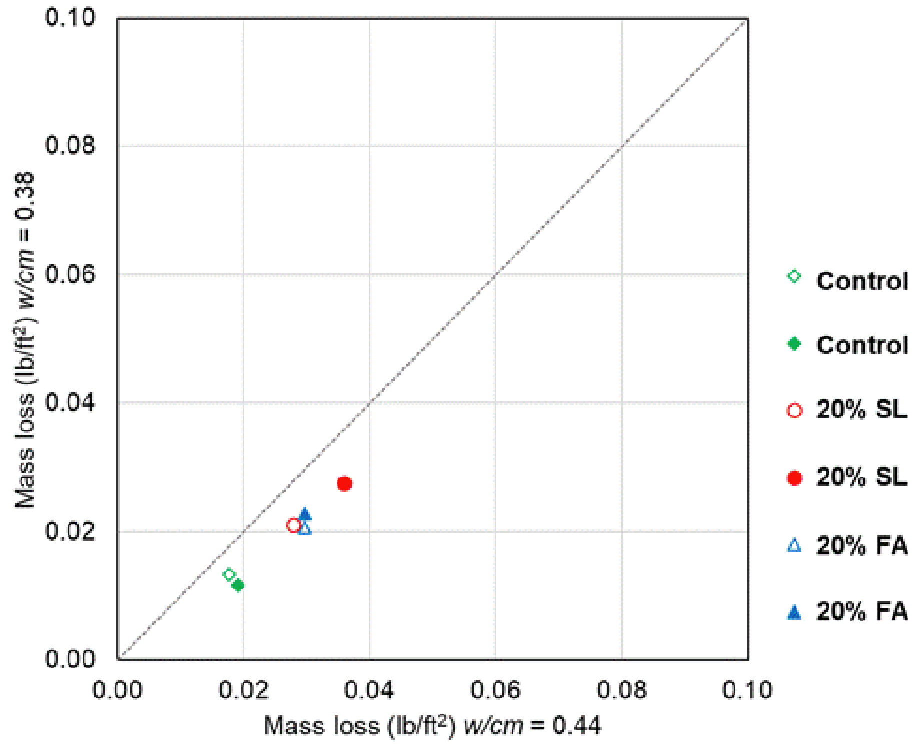

Figure 3.14: Comparison of average cumulative mass losses for mixtures *w/cm* ratios of 0.38 and 0.44 exposed to NaCl. Hollow markers represent specimens with 14 days of curing and shaded markers represent specimens with 28 days of curing

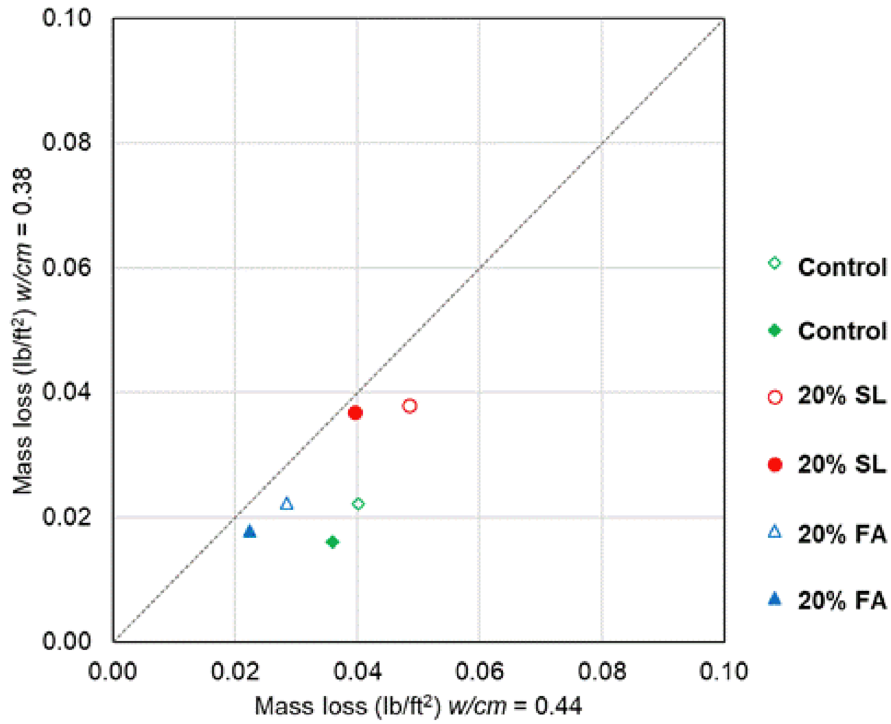

Figure 3.15: Comparison of average cumulative mass losses for mixtures *w/cm* ratios of 0.38 and 0.44 exposed to CaCl2. Hollow markers represent specimens with 14 days of curing and shaded markers represent specimens with 28 days of curing

3.5 SUMMARY AND CONCLUSIONS

In this study, 156 specimens representing 10 concrete mixtures were cast and tested in accordance with the Quebec Test BNQ NQ 2621-900 to investigate the effects of percentage replacement of portland cement with SCMs (20%, 35%, or 50% by volume), deicing salt type (NaCl or $CaCl_2$), curing period (14 or 28 days), and water-to-cementitious material ratio (0.38 or 0.44) on the scaling resistance of concrete.

The following conclusions are based on the results and analysis described in this chapter.

1. Using slag cement or Class C fly ash as a replacement of portland cement results in an increase in scaling compared to concrete mixtures with 100% portland cement. For mixtures with 50% replacements, the increase in scaling is noticeably higher than for mixtures with 20% and 35% replacements, especially so for mixtures exposed to NaCl.

2. Under exposure to NaCl, mixtures incorporating slag cement had comparable mass losses to those incorporating Class C fly ash. Under exposure to $CaCl_2$, mixtures incorporating slag cement had slightly higher mass loss than mixtures incorporating Class C fly ash.
3. A 35% replacement with either slag cement or Class C fly ash resulted in scaling below the failure limit of BNQ NQ 2621-900 and may serve as a safe maximum allowable replacement value for durable concrete.
4. $CaCl_2$ caused 11% to 151% more scaling than NaCl for concrete mixtures with 100% portland cement and concrete mixtures with 20% of slag cement.
5. NaCl caused 21% to 118% more scaling than $CaCl_2$ for concrete mixtures with 35% replacements of slag cement or Class C fly ash for portland cement. In all cases, however, the mass losses for mixtures with 35% SCMs were below the BNQ NQ 2621-900 failure limit of 0.10 lb/ft^2 and well below the MTO failure limit of MTO 0.16 lb/ft^2.
6. NaCl caused 55% to 217% more scaling than $CaCl_2$ for concrete mixtures with 50% cement replacements with slag cement or Class C fly ash. The mass losses for mixtures with 50% SCMs exposed to NaCl were above the BNQ NQ 2621-900 failure limit of 0.10 lb/ft^2 and close or above the MTO failure limit of 0.16 lb/ft^2.
7. Extending the curing period from 14 to 28 days has no measurable effect on the scaling for most concrete mixtures in the study. The exception in the current study was concrete with a 50% replacement of Class C fly ash for portland cement, which exhibited an increase in mass loss with an increase in curing period.
8. Reducing the *w/cm* ratio, in the current study from 0.44 to 0.38, reduces scaling of concrete mixtures.

CHAPTER 4 - EVALUATING THE DURABILITY OF CONCRETE INCORPORATING SLAG CEMENT OR CLASS C FLY ASH

4.1 INTRODUCTION

The use of deicing salts has been shown to cause durability problems in concrete due to chemical reactions between deicing salts and concrete (Chapter 2) and scaling (Chapter 3). Prior laboratory tests have yielded mixed results on the effects of supplementary cementitious materials (SCMs) on the resistance of concrete to deicing salts. Some studies have found that using SCMs has reduced durability due to increased scaling (Bouzoubaâ et al. 2011, Hooton and Vassilev 2012). Other studies, however, have found that using SCMs provide improved durability due to decreased chloride penetration (Mindess et al. 2003) and a reduction in the formation of calcium oxychloride (Jain et al. 2012, Suraneni et al. 2016, Ghazy and Bassuoni 2017).

Prior studies have examined the effect of SCMs on either scaling resistance or resistance to chemical attack under wetting and drying cycles in the presence of deicing salts, but not both simultaneously. This is problematic because using increasing percentages of SCMs tends to increase scaling damage but reduce damage from wetting and drying cycles. Therefore, there is an essential need to establish a reasonable range of replacement percentages of SCMs to ensure a balance in performance against both scaling and damage due to exposure to wetting and drying cycles.

This chapter evaluates the durability of concrete mixtures against both scaling damage and exposure to deicing salts under wetting and drying cycles. Furthermore, this chapter compares the scaling results of this study with the results of prior studies.

4.2 EVALUATING THE DURABILITY OF CONCRETE MIXTURES

This section evaluates the durability of concrete mixtures based on wetting and drying and scaling tests, as described in Chapters 2 and 3.

4.2.1 Wetting and drying test

Table 2.4, repeated here as Table 4.1, summarizes the wetting and drying results from this study, which are described in detail in Chapter 2. The table shows the average relative dynamic modulus at 300 cycles for specimens exposed to deionized water (DI water) or the salt solutions NaCl, $CaCl_2$, or $MgCl_2$ in the current study. Yellow shading indicates that the specimens exhibited spalling. Regardless of the *w/cm* ratio and the concrete mixture, exposure to DI water or NaCl did not result in damage to the concrete. The specimens that exhibited spalling were those incorporating 100% portland cement exposed to either the $CaCl_2$ or $MgCl_2$ solutions and those incorporating 20% of either slag cement or Class C fly ash as replacements for portland cement exposed to the $CaCl_2$ solution. No spalling was observed for specimens incorporating 35% or 50% of either slag cement or Class C fly ash. Based on these observations, the mixtures that exhibited no spalling after 300 cycles of wetting and drying under exposure to $CaCl_2$ or $MgCl_2$ are considered to be durable under these conditions that result in the formation of calcium oxychloride.

Table 4.1: Average relative dynamic modulus of elasticity after 300 cycles in the wetting and drying test (current study)

	Solution			
Mixture	DI water	NaCl	$CaCl_2$	$MgCl_2$
Control-0.38	1.05	1.02	0.68	0.86
20% SL-0.38	1.05	1.03	0.89	0.96
35% SL-0.38	1.05	1.03	0.97	0.97
50% SL-0.38	1.05	1.03	0.99	0.98
20 % FA-0.38	1.06	1.02	0.92	0.96
35 % FA-0.38	1.07	1.04	0.97	0.95
50 % FA-0.38	1.08	1.05	1.00	0.96
Control-0.44	1.06	1.03	0.53	0.85
20% SL-0.44	1.04	1.03	0.87	0.94
35% SL-0.44	1.05	1.03	0.94	0.95
50% SL-0.44	1.04	1.02	0.96	0.95
20 % FA-0.44	1.06	1.04	0.90	0.92
35 % FA-0.44	1.09	1.05	0.99	0.95
50 % FA-0.44	1.13	1.08	1.00	0.97

Highlighted values indicate spalling

4.2.2 Scaling test

Table 4.2 shows the average cumulative mass loss at 56 cycles for the specimens in the current study, summarizing the results from Chapter 3. Full comparisons were made for mixtures with *w/cm* ratios of 0.44, but not 0.38. Yellow shading indicates that the specimens had mass loss greater than or equal to the failure limit of BNQ NQ 2621-900 of 0.1 lb/ft^2 (500 g/m^2). Regardless of the curing period and deicing salt type, concrete mixtures with 100% portland cement, 20% or 35% slag cement, or 20% or 35% Class C fly ash had mass losses below the failure limit of BNQ NQ 2621-900. For mixtures with 100% portland cement, the mass losses ranged from 0.01 to 0.05 lb/ft^2, and for mixtures with 20% or 35% slag cement or Class C fly ash, mass losses ranged from 0.02 to 0.07 lb/ft^2. Concrete mixtures incorporating 50% slag cement or Class C fly ash, however, had noticeably higher mass losses than the other mixtures, with losses ranging from 0.15 to 0.27

lb/ft^2 when exposed to NaCl. These mixtures also had the highest mass losses when exposed to $CaCl_2$, with losses ranging from 0.05 to 0.11 lb/ft^2

Table 4.2: Average cumulative scaling mass loss at 56 cycles (lb/ft^2) of concrete specimens with different replacement percentages of SCMs

Mixtures	Type of salt – curing period			
	NaCl - 14 days	NaCl - 28 days	$CaCl_2$ – 14 days	$CaCl_2$ - 28 days
Control-0.38	0.01	0.01	0.02	0.02
20% SL-0.38	0.02	0.03	0.04	0.04
35% SL-0.38	--	--	--	--
50% SL-0.38	--	--	--	--
20 % FA-0.38	0.02	0.02	0.02	0.02
35 % FA-0.38	--	--	--	--
50 % FA-0.38	--	--	--	--
Control-0.44	0.02	0.02	0.04	0.04
Control-RE-0.44	0.02	0.02	0.04	0.05
20% SL-0.44	0.03	0.04	0.05	0.04
35% SL-0.44	0.06	0.07	0.03	0.03
50% SL-0.44	0.20	0.18	0.09	0.08
50% SL-RE-0.44	0.19	0.16	0.11	0.10
20 % FA-0.44	0.03	0.03	0.03	0.02
35 % FA-0.44	0.05	0.05	0.03	0.04
50 % FA-0.44	0.15	0.27	0.06	0.08
50 % FA-RE-0.44	0.15	0.20	0.05	0.07

Highlighted values indicate mass loss greater than or equal to the failure limit of BNQ NQ 2621-900 of 0.1 lb/ft^2 (500 g/m^2)

Tables 4.3 and 4.4 compare the mass losses measured in the current study with those in prior studies. For the selected prior studies, specimens were cured for 14 days and tested in accordance with BNQ NQ 2621-900 under exposure to NaCl. To ensure a fair comparison, only the mass losses for specimens cured for 14 days and exposed to NaCl in the current study are included. In the study by Hooton and Vassilev (2012), two types of portland cement (low alkali or high alkali), also two grades of slag cement (Grade 100 or Grade 120) were used. In this case, only the mass losses for specimens from mixtures with low alkali cement and Grade 100 slag cement are included.

Table 4.3 compares the mass losses for concrete with 100% portland cement. The results from the current study show that these specimens performed well, following the trend in prior studies. An exception is noted in the study by Ibrahim, Darwin, and O'Reilly (2019), where the one mixtures exhibited a mass loss of 0.12 lb/ft^2. This is relatively high compared with mass losses of the other mixtures containing 100% portland cement and is likely an outlier.

Table 4.3: Scaling mass losses of concrete with 100% portland cement

Study	***w/cm***	**Concentration and type of salt**	**Mass loss (lb/ft^2)**
Hooton and Vassilev (2012)	0.42	3.0% NaCl	0.02
			0.02
			0.03
Pendergrass and Darwin (2014)	0.45	2.5% NaCl	0.03
			0.01
			0.01
Ibrahim et al. (2019)	0.45	2.5% NaCl	0.12
	0.45		0.04
	0.42		0.03
Current study	0.38	3.0% NaCl	0.01
	0.44	3.0% NaCl	0.02
			0.02

Table 4.4 compares scaling mass losses with different replacement percentages of SCMs. In the studies by Bouzoubaâ et al. (2008), Bouzoubaâ et al. (2011), and Hooton and Vassilev (2012), SCM replacements were based on the weight of portland cement, while in the current study and that by Ibrahim et al. (2019), SCM replacements were based on the volume of portland cement. Mass losses in the current study and those from the studies by Bouzoubaâ et al. (2008), Bouzoubaâ et al. (2011), and Hooton and Vassilev (2012) reveal that replacing 20%, 25%, or 35% of portland cement with an SCM results in mass losses below the failure limit of BNQ NQ 2621-900. Mass losses measured by Ibrahim et al. (2019) show that the concrete mixture with 20% Class F fly ash had a mass loss of 0.05 lb/ft^2, below the BNQ NQ 2621-900 failure limit of 0.1 lb/ft^2; the concrete mixture with 20% Class C fly ash, however, had a mass loss of 0.19 lb/ft^2. The high mass loss for

mixture with 20% Class C fly ash is in contrast to the findings of a prior study by Sobolev et al. (2017), where concrete mixtures with Class C fly ash had less mass loss than concrete mixtures with Class F fly ash.

At high replacement percentages (40% and above) of portland cement with SCMs, Hooton and Vassilev (2012), Ibrahim et al. (2019), and the current study show that concrete mixtures exhibit mass losses exceeding the BNQ NQ 2621-900 failure limit of 0.1 lb/ft^2. This suggests that replacing portland cement with SMCs more than 35% by volume is not a recommended approach to produce durable concrete that will be exposed to NaCl.

Table 4.4: Scaling mass losses of concrete with different replacement percentages of SCMs

Study	*w/cm*	% SCMs, type	Concentration and type of salt	Mass loss (lb/ft^2)
Bouzoubaâ et al. (2008) †	0.41	25% Class F fly ash	3.0% NaCl	0.07
	0.41	35% Class F fly ash		0.07
	0.42	35% slag cement		0.05
Bouzoubaâ et al. (2011) †	0.45	25% Class F fly ash	3.0% NaCl	0.09
Hooton and Vassilev (2012) †	0.42	20% slag cement	3.0% NaCl	0.02
		20% slag cement		0.02
		35% slag cement		0.05
		50% slag cement		0.31
Ibrahim et al. (2019) *	0.45	20% Class F fly ash	2.5% NaCl	0.05
		20% Class C fly ash		0.19
		40% Class F fly ash		0.15
		40% Class F fly ash		0.14
Current study *	0.38	20% slag cement	3.0% NaCl	0.02
		20% Class C fly ash		0.02
	0.44	20% slag cement		0.03
		35% slag cement		0.06
		50% slag cement		0.20
		50% slag cement		0.19
		20% Class C fly ash		0.03
		35% Class C fly ash		0.05
		50% Class C fly ash		0.15
		50% Class C fly ash		0.15

† SCMs replaced by weight of portland cement
* SCMs replaced by volume of portland cement

Table 4.5 summarizes the results for both the wetting and drying and scaling tests from the current study. In the wetting and drying test, if specimens exposed to $CaCl_2$ or $MgCl_2$ exhibited spalling, the concrete is considered to have failed. If the average cumulative mass loss in the scaling test is greater than or equal to the failure limit of BNQ NQ 2621-900 of 0.1 lb/ft^2 (500 g/m^2), the concrete is also considered to have failed.

Table 4.5: Evaluating the durability of concrete mixtures (current study)

Mixtures	**Wetting and drying**			**Scaling**			
	Type of salt			**Type of salt – curing period**			
	NaCl	$CaCl_2$	$MgCl_2$	NaCl - 14 days	NaCl - 28 days	$CaCl_2$ - 14 days	$CaCl_2$ - 28 days
Control-0.38	Pass	Fail	Fail	Pass	Pass	Pass	Pass
20% SL-0.38	Pass	Fail	Pass	Pass	Pass	Pass	Pass
35% SL-0.38	Pass	Pass	Pass	--	--	--	--
50% SL-0.38	Pass	Pass	Pass	--	--	--	--
20 % FA-0.38	Pass	Fail	Pass	Pass	Pass	Pass	Pass
35 % FA-0.38	Pass	Pass	Pass	--	--	--	--
50 % FA-0.38	Pass	Pass	Pass	--	--	--	--
Control-0.44	Pass	Fail	Fail	Pass	Pass	Pass	Pass
Control-RE-0.44	--	--	--	Pass	Pass	Pass	Pass
20% SL-0.44	Pass	Fail	Pass	Pass	Pass	Pass	Pass
35% SL-0.44	Pass	Pass	Pass	Pass	Pass	Pass	Pass
50% SL-0.44	Pass	Pass	Pass	Fail	Fail	Pass	Pass
50% SL-RE-0.44	--	--	--	Fail	Fail	Fail	Fail
20 % FA-0.44	Pass	Fail	Pass	Pass	Pass	Pass	Pass
35 % FA-0.44	Pass	Pass	Pass	Pass	Pass	Pass	Pass
50 % FA-0.44	Pass	Pass	Pass	Fail	Fail	Pass	Pass
50 % FA-RE-0.44	--	--	--	Fail	Fail	Pass	Pass

Highlighted values indicate that specimens exhibit spalling in the wetting and drying test or mass loss greater than or equal to the failure limit of BNQ NQ 2621-900 in the scaling test

Based on the acceptance criteria tied to Tables 4.1 and 4.5, using SCMs as a 20% replacement of portland cement was not sufficient to produce durable concrete under conditions that will result in the formation of calcium oxychloride, while using SCMs at 35% or 50% as replacements was. Replacement percentages between 20% and 35%, which were not included in the current study, may also be sufficient. Increasing the replacement percentage from 35% to 50%

resulted in only a slight increase in the average relative dynamic moduli at the end of testing (1% to 3%). Using SCMs at a 50% replacement of portland cement, however, resulted high scaling losses, as shown in Tables 4.2 and 4.5. Therefore, replacing portland cement with more than a 35% SCM replacement of portland cement is not recommended, while volume replacements of portland of 35% by volume, corresponding to 33% by weight for slag cement and 31% by weight for Class C fly ash (based on respective specific gravities of 3.14, 2.89, and 2.63 in this study), are considered as appropriate to provide good durability against both calcium oxychloride formation and scaling in the presence of NaCl, $CaCl_2$, and $MgCl_2$. Replacement percentages above 20%, but below 35%, may also prove to be viable. The poor performance of the mixtures containing 20% replacements when oxychloride formation occurs, however, suggests that percentages closer to 35% would be the better choice.

CHAPTER 5 - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 SUMMARY

The effects of deicing salts on the durability of concrete incorporating supplementary cementitious materials (SCMs) are evaluated using a wetting and drying test and a scaling test.

For the wetting and drying test, 14 concrete mixtures (204 specimens) were cast to evaluate damage in concrete subjected to 300 cycles of wetting and drying while exposed to deicing salts in which the temperature of the specimens ranged from a low of 39.2 ºF (4 ºC) during the wetting cycle to a high of 73 ± 3 ºF (23 ± 2 ºC) during the drying cycle. The study evaluates the effects of deicing salt type (NaCl, $CaCl_2$, or $MgCl_2$) and deionized water, water-to-cementitious material ratio (0.38 or 0.44), and percentage replacement (20%, 35%, or 50% by volume) of cement with slag cement or Class C fly ash. Emphasis was placed on the effects of $CaCl_2$ and $MgCl_2$, which result in the formation of calcium oxychloride. Specimens were monitored throughout the test based on the average relative dynamic modulus of elasticity and the nature of physical damage, if any. Acceptance criteria of mixture proportions are based on the visual inspection of specimens at the end of the test. Mixtures that exhibit no spalling after 300 cycles of wetting and drying with solutions of $CaCl_2$ or $MgCl_2$ are considered to be durable under conditions that result in the formation of calcium oxychloride.

For the scaling test, 10 concrete mixtures (156 specimens) were cast and tested to investigate the effects of percentage replacement (20%, 35%, or 50% by volume) of cement with slag cement or Class C fly ash, deicing salt type (NaCl or $CaCl_2$), curing period (14 or 28 days), and water-to-cementitious material ratio (0.38 or 0.44) on scaling resistance through 56 cycles using the BNQ NQ 2621-900 test. At the end of the test, the average cumulative mass losses are compared with the BNQ NQ 2621-900 failure limit of 0.10 lb/ft^2 and the MTO failure limit of 0.16

lb/ft^2. Mixtures are considered durable if the average cumulative mass losses are less than the BNQ NQ 2621-900 failure limit.

5.2 CONCLUSIONS

The following conclusions are based on the test results and analyses described in this report.

5.2.1 Effects of deicing salts on concrete incorporating slag cement or Class C fly ash (wetting and drying test)

1. Based on the average relative dynamic modulus and visual inspection after 300 cycles of wetting and drying, exposure to deionized water or NaCl does not cause deterioration to concrete.
2. $CaCl_2$ causes more damage and a greater reduction in the average relative dynamic modulus of elasticity to concrete in which portland cement as the only binder than the other deicing salts. $MgCl_2$ also results in damage to concrete with 100% portland cement, but less so than $CaCl_2$.
3. Increasing the replacement percentage of portland cement with slag cement or Class C fly ash provides increased resistance of concrete to $CaCl_2$ or $MgCl_2$. This improvement can be tied to the reduction in available $Ca(OH)_2$, which, in turn, reduces the quantity of calcium oxychloride formed at lower temperatures.
4. Based on the acceptance criteria, replacing 20% of portland cement with an SCM is not sufficient to produce durable concrete under conditions that result in the formation of calcium oxychloride, while replacing 35% or 50% of portland cement with the SCMs used in this study is.

5. Increasing the replacement percentage of SCMs from 35% to 50% results in only a slight increase in the average relative dynamic moduli (1% to 3%).
6. Chloride ions do not penetrate as far when concrete is exposed to $MgCl_2$ as when concrete is exposed to $CaCl_2$ or NaCl, suggesting that magnesium hydroxide $Mg(OH)_2$ (brucite), which has low permeability, forms in the specimens.
7. Reducing the *w/cm* ratio does not have a clear impact on the durability of concrete containing SCMs under exposure to the wetting and drying cycles but is effective in reducing damage to concrete in which portland cement as the only binder. Using a *w/cm* ratio as low as 0.38 when portland cement as the only binder, however, is not adequate to produce durable concrete under conditions that result in the formation of calcium oxychloride.

5.2.2 Scaling resistance of concrete containing slag cement or Class C fly ash

1. Using slag cement or Class C fly ash as a replacement of portland cement results in an increase in scaling compared to concrete mixtures with portland cement as the only binder. At 50% volume replacements, the increase in scaling is noticeably higher compared to 20% and 35% replacements, especially so for mixtures exposed to NaCl.
2. Under exposure to NaCl, mixtures incorporating slag cement exhibits comparable mass losses to those incorporating Class C fly ash. Under exposure to $CaCl_2$, mixtures incorporating slag cement had slightly mass loss than mixtures incorporating Class C fly ash.
3. A 35% replacement with either slag cement or Class C fly ash resulted in scaling below the failure limit of BNQ NQ 2621-900 and may serve as a safe maximum allowable replacement value for durable concrete.

4. $CaCl_2$ causes more scaling than NaCl for concrete mixtures with portland cement as the only binder and concrete mixtures with a 20% of slag cement replacement of portland cement.
5. NaCl causes more scaling than $CaCl_2$ for concrete mixtures with 35% cement replacements with slag cement or Class C fly ash. In all cases, however, the mass losses for mixtures with 35% SCMs were below the BNQ NQ 2621-900 failure limit of 0.10 lb/ft^2 and well below the MTO failure limit of MTO 0.16 lb/ft^2.
6. NaCl causes more scaling than $CaCl_2$ for concrete mixtures with 50% cement replacements with slag cement or Class C fly ash. The mass losses for mixtures with 50% SCMs exposed to NaCl were above the BNQ NQ 2621-900 failure limit of 0.10 lb/ft^2 and close to or above the MTO failure limit of 0.16 lb/ft^2.
7. Extending the curing period from 14 to 28 days has no measurable effect on the scaling for most concrete mixtures in the study. The exception in the current study was concrete with a 50% replacement of Class C fly ash for portland cement, which exhibited an increase in mass loss with an increase in curing period.
8. Reducing the *w/cm* ratio, in the current study from 0.44 to 0.38, reduces scaling of concrete mixtures.

5.3 RECOMMENDATIONS

1. A partial replacement of portland cement with either slag cement or Class C fly ash is essential to produce durable concrete that will be subjected to the deicing salts $CaCl_2$ or $MgCl_2$ to limit the formation of calcium oxychloride. Using a 20% volume replacement of portland cement is not adequate while a 35% volume replacement is. Replacement percentages above 35% are not recommended when the deicing salt NaCl

may be used because of increasingly poor scaling resistance with increasing slag cement and Class C fly ash replacement levels.

2. Further wetting and drying tests are recommended to investigate the behavior of concrete mixtures incorporating SCMs at cement replacements between 20% to 35% to determine if a replacement level below 35% will provide adequate durability.

REFERENCES

ACI Committee 201. (2016). "*Guide to Durable Concrete*," ACI 201.2R-16, American Concrete Institute, Farmington Hills, MI, 62 pp.

ACI Committee 232. (2018). "*Report on the Use of Fly Ash in Concrete*," ACI 232.2R-18, American Concrete Institute, Farmington Hills, MI, 55 pp.

ACI Committee 233. (2017). "*Guide to the Use of Slag Cement in Concrete and Mortar*," ACI 233R-17, American Concrete Institute, Farmington Hills, MI, 24 pp.ASCE. (2017). *Report Card for America's Infrastructure,* https://www.infrastructurereportcard.org/wp-content/uploads/2017/01/Bridges-Final.pdf (accessed 20 June 2019)

ASTM C 215-14 (2014). "*Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens*," ASTM International, West Conshohocken, PA, 7 pp.

ASTM C 989-05 (2005). "*Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars*," ASTM International, West Conshohocken, PA, 5 pp.

ASTM C618-05 (2005). "*Standard Specification for Coal Fly Ash and Raw or Calcined* Natural Pozzolan for Use in Concrete," ASTM International, West Conshohocken, PA, 3 pp.

Bilodeau, A., Carette, G. G., and Malhotra, V. M. (1991). "Influence of Curing and Drying on Salt Scaling Resistance of Fly Ash Concrete," *ACI Special Publication*, Vol. 126, pp. 201-228.

Bilodeau, A., Zhang, M. H., Malhotra, V. M., and Golden, D. M. (1998). "Effect of Curing Methods and Conditions on the Performance of Fly Ash Concrete in De-king Salt Scaling," *ACI Special Publication*, Vol. 178, pp. 361-384.

Birnin-Yauri, U. A., and Glasser, F. P. (1998). "Friedel's Salt, $Ca_2Al(OH)_6(Cl,OH)\cdot 2H_2O$: its Solid Solutions and Their Role in Chloride Binding," *Cement and Concrete Research*, Vol. 28, No. 12, pp. 1713-1723.

Bouzoubaâ, N., Bilodeau, A., Fournier, B., Hooton, R. D., Gagné, R., and Jolin, M. (2008). "Deicing Salt Scaling Resistance of Concrete Incorporating Supplementary Cementing Materials: Laboratory and Field test data," *Canadian Journal of Civil Engineering,* Vol. 35, No. 11, pp. 1261-1275.

Bouzoubaâ, N., Bilodeau, A., Fournier, B., Hooton, R., Gagné, R., and Jolin, M. (2011). "Deicing Salt Scaling Resistance of Concrete Incorporating Fly Ash and (or) Silica Fume: Laboratory and Field Sidewalk Test Data," *Canadian Journal of Civil Engineering,* Vol. 38, No. 4, pp. 373-382.

Collepardi, M., Coppola, L., and Pistolesi, C. (1994). "Durability of Concrete Structures Exposed to $CaCl_2$ Based Deicing Salts," *ACI Special Publication*, Vol. 145, pp. 107-120.

Darwin, D., Browning, J., Gong, L., and Hughes, S. R. (2008). "Effects of Deicers on Concrete Deterioration," *ACI Materials Journal,* Vol. 105, No. 6, pp. 622-627.

Farnam, Y., Dick, S., Wiese, A., Davis, J., Bentz, D., and Weiss, J. (2015a). "The Influence of Calcium Chloride Deicing Salt on Phase Changes and Damage Development in Cementitious Materials," *Cement and Concrete Composites*, Vol. 64, pp. 1-15.

Farnam, Y., Wiese, A., Bentz, D., Davis, J., and Weiss, J. (2015b). "Damage Development in Cementitious Materials Exposed to Magnesium Chloride Deicing Salt," *Construction and Building Materials*, Vol. 93, pp. 384-392.

Ghazy, A. and Bassuoni, M.T. (2017). "Resistance of Concrete to Different Exposures with Chloride-Based Salts," *Cement and Concrete Research,* Vol. 101, pp. 144-158.

Hooton, R. and Vassilev, D. (2012). "Deicer Scaling Resistance of Concrete Mixtures Containing Slag Cement Phase 2: Evaluation of Different Laboratory Scaling Test Methods," National Concrete Pavement Technology Center, Iowa State University, 48 pp.

Houehanou, E., Gagné, R., and Jolin, M. (2010). "Analysis of the Representativeness and Relative Severity of ASTM C672 and NQ 2621-900 Standard Procedures in Evaluating Concrete Scaling Resistance," *Canadian Journal of Civil Engineering,* Vol. 37, No. 11, pp. 1471-1482.

Ibrahim, E., Darwin, D., and O'Reilly, M. (2019). "Effect of Crack-Reducing Technologies and Supplementary Cementitious Materials on Settlement Cracking of Plastic Concrete and Durability Performance of Hardened Concrete," *SM Report* No. 134, University of Kansas Center for Research, Inc., Lawrence, KS, 268 pp.

Jain, J., Olek, J., Janusz, A., and Jozwiak-Niedzweidzka, D. (2012). "Effects of Deicing Salt Solutions on Physical Properties of Pavement Concretes," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2290, pp. 69-75.

Jones, W., Farnam, Y., Imbrock, P., Spiro, J., Villani, C., Olek, J., and Weiss, W. J. (2013). "An Overview of Joint Deterioration in Concrete Pavement: Mechanisms, Solution Properties, and Sealers," Purdue University, West Lafayette, IN, 58 pp.

Julio-Betancourt G. A. (2009). "Effect of De-Icers and Anti-Icer Chemicals on the Durability, Microstructure, and Properties of Cement-Based Materials," Doctoral dissertation, University of Toronto.

Khajehdehi, R. and Darwin, D. (2018). "Controlling Cracks in Bridge Decks," *SM Report* No. 129, University of Kansas Center for Research, Inc., Lawrence, KS, 218 pp.

Kulik, D., Wagner, T., Dmytrieva, S., Kosakowski, G., Hingerl, F., Chudnenko, K., and Berner, U. (2013). "GEM-Selektor Geochemical Modeling Package: Revised Algorithm and GEMS3K Numerical Kernel for Coupled Simulation Codes," *Computational Geosciences*, Vol. 17, pp. 1-24.

Lindquist, W., Darwin, D., and Browning, J. (2008). "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage, Mixture Optimization, and Concrete Production," *SM Report* No. 92, The University of Kansas Center for Research, Inc., Lawrence, Kansas, 540 pp.

McLeod, H., Darwin, D., and Browning, J. (2009). "Development and Construction of Low-

Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Construction Methods, Specifications, and Resistance to Chloride Ion Penetration," *SM Report* No. 94, The University of Kansas Center for Research, Inc., Lawrence, KS, 848 pp.

Mesbah, A., François, M., Cau-dit-Coumes, C., Frizon, F., Filinchuk, Y., Leroux, F., Ravaux, J. and Renaudin, G. (2011). "Crystal Structure of Kuzel's Salt $3CaO{\cdot}Al_2O_3{\cdot}½CaSO_4{\cdot}½CaCl_2{\cdot}11H_2O$ Determined by Synchrotron Powder Diffraction," *Cement and Concrete Research*, Vol. 41, No. 5, pp. 504-509.

Mindess, S., Young, F., and Darwin, D. (2003). *Concrete*, second edition, Prentice Hall., Englewood Cliffs, NJ, 644 pp.

Ozyildirim, C. (1998). "Effects of Temperature on the Development of Low Permeability in Concretes," VTRC R98-14, Virginia Transportation Research Council, Charlottesville, VA, 22 pp.

Pendergrass, B., and Darwin, D. (2014). "Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Shrinkage-Reducing Admixtures, Internal Curing, and Cracking Performance," *SM Report* No. 107, University of Kansas Center for Research, Inc. Lawrence, KS, 664 pp.

Pigeon, M., and Pleau, R. (1995). *Durability of Concrete in Cold Climates*, E and FN Spon, London, 240 pp.

Qiao, C., Suraneni, P., and Weiss, J. (2017). "Measuring Volume Change Caused by Calcium Oxychloride Phase Transformation in a $Ca(OH)_2$-$CaCl_2$-H_2O System," *Advances in Civil Engineering Materials,* Vol. 6, No. 1, pp. 157-169.

Qiao, C., Suraneni, P., and Weiss, J. (2018a). "Damage in Cement Pastes Exposed to NaCl Solutions," *Construction and Building Materials*, Vol. 171, pp. 120-127.

Qiao, C., Suraneni, P., Chang, M. T., and Weiss, J. (2018b). "Damage in Cement Pastes Exposed to $MgCl_2$ Solutions," *Materials and Structures*, Vol. 51, No.3, pp. 1-15.

Schlorholtz, S., and Hooton, R. (2008). "Deicer Scaling Resistance of Concrete Pavements, Bridge Decks, and Other Structures Containing Slag Cement, Phase 1: Site Selection and Analysis of Field Cores," National Concrete Pavement Technology Center, Iowa State University, 49 pp.

Shi, X., Fay, L., Peterson, M. M., Berry, M., and Mooney, M. (2011). "A FESEM/EDX Investigation into How Continuous Deicer Exposure Affects the Chemistry of Portland Cement Concrete," *Construction and Building Materials*, Vol. 25, No. 2, pp. 957-966.

Sobolev, K., Moini, M., Tabatabai, H., Titi, H. H., Pradoto, R., Kozhukhova, M., Flores-Vivian, I. and Muzenski, S. (2017) "Class F Fly Ash Assessment for Use in Concrete Pavements," No. WHRP 0092-15-10, Wisconsin Highway Research Program.

Suraneni, P., Azad, V., Isgor, O., and Weiss, J. (2016). "Calcium Oxychloride Formation in Pastes Containing Supplementary Cementitious Materials: Thoughts on the Role of Cement and Supplementary Cementitious Materials Reactivity," *RILEM Technical Letters,* pp. 24-30.

Sutter, L., Peterson, K., Julio-Betancourt, G., Hooton, D., Dam, T. V., and Smith, K. (2008). "The Deleterious Chemical Effects of Concentrated Deicing Solutions on Portland Cement Concrete," South Dakota Department of Transportation, Office of Research, 198 pp.

Sutter, L., Peterson, K., Touton, S., Van Dam, T., and Johnston, D. (2006). "Petrographic Evidence of Calcium Oxychloride Formation in Mortars Exposed to Magnesium Chloride Solution," *Cement and Concrete Research*, Vol. 36, No. 6, pp. 1533-1541.

Talbot, C., Pigeon, M., and Marchand, J. (1996). "Influence of Supplementary Cementing Materials on the Deicer Salt Scaling Resistance of Concrete," In *Proc. of the 7th Int. Conf. on the Durability of Building Materials and Components*.

Valenza II, J. (2005). "Mechanism for Salt Scaling," Doctoral dissertation, Princeton University.

Verbeck, G. and Klieger, P. (1957). "Studies of 'Salt' Scaling," *Bulletin 83*, *Portland Cement* Association, Chicago, IL, 13 pp.

Yuan, J., Darwin, D., Browning, J. (2011). "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage Tests, Restrained Ring Tests, Construction Experience, and Crack Survey Results," *SM Report* No. 103, The University of Kansas Center for Research, Inc., Lawrence, KS, 505 pp.

APPENDIX A: WETTING AND DRYING TEST DATA FOR MIXTURES IN CHAPTER 2

Table A.1: Mass, frequency, and moduli of elasticity of Control-0.38 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4220.5	4205.5	4227.7	3065	3049	3035	6453	6363	6338	6385	60	0.009
17	4218.3	4203.1	4224.2	3067	3049	3025	6458	6359	6291	6369	84	0.013
28	4219.0	4204.5	4225.4	3080	3057	3048	6514	6395	6389	6433	70	0.011
43	4218.8	4204.8	4226.2	3094	3074	3054	6573	6467	6415	6485	80	0.012
56	4218.5	4205.0	4226.0	3097	3077	3055	6585	6480	6419	6495	84	0.013
70	4218.8	4205.4	4226.4	3103	3082	3055	6585	6480	6419	6495	84	0.013
85	4220.1	4206.1	4226.3	3108	3086	3062	6635	6519	6449	6534	94	0.014
98	4221.0	4207.5	4226.8	3111	3091	3070	6649	6543	6484	6558	84	0.013
113	4221.2	4208.4	4226.6	3114	3094	3079	6662	6557	6521	6580	73	0.011
126	4222.1	4207.3	4227.7	3116	3096	3087	6672	6563	6557	6597	65	0.010
141	4222.4	4207.4	4228.9	3120	3099	3093	6690	6576	6584	6617	63	0.010
154	4222.5	4208.5	4229.8	3124	3105	3100	6707	6604	6616	6642	56	0.009
170	4222.9	4209.8	4231.4	3130	3109	3105	6733	6623	6639	6665	60	0.009
184	4222.0	4208.0	4228.5	3134	3113	3105	6749	6637	6635	6674	65	0.010
196	4223.8	4207.9	4230.3	3134	3112	3093	6752	6632	6587	6657	85	0.013
210	4225.1	4208.3	4231.1	3136	3110	3086	6763	6625	6558	6648	104	0.016
224	4225.9	4209.8	4232.6	3137	3106	3092	6768	6610	6586	6655	99	0.015
238	4226.5	4211.6	4234.1	3136	3108	3090	6765	6621	6580	6655	97	0.015
252	4226.9	4213.0	4234.2	3135	3105	3096	6761	6611	6605	6659	88	0.013
266	4226.3	4213.2	4233.5	3138	3109	3102	6773	6628	6630	6677	83	0.012
280	4225.8	4212.3	4234.1	3140	3112	3109	6781	6639	6661	6694	76	0.011
294	4225.6	4211.5	4234.9	3139	3116	3114	6776	6655	6684	6705	63	0.009
300	4225.0	4210.0	4230.0	3140	3115	3117	6780	6649	6689	6706	67	0.010

*i** means initial reading after 28 days of curing

Table A.2: Mass, frequency, and moduli of elasticity of Control-0.38 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4278.9	4247.0	4224.2	3084	3055	3059	6624	6451	6433	6503	105	0.016
17	4278.1	4247.0	4225.0	3064	3030	3035	6537	6346	6334	6405	114	0.018
28	4279.3	4247.5	4226.0	3074	3041	3044	6581	6393	6373	6449	115	0.018
43	4280.4	4249.0	4228.4	3092	3056	3052	6660	6458	6410	6510	133	0.020
56	4281.1	4249.8	4229.1	3091	3060	3057	6657	6476	6432	6522	119	0.018
70	4282.0	4250.6	4230.0	3091	3063	3061	6658	6490	6451	6533	110	0.017
85	4283.1	4251.7	4228.5	3093	3068	3069	6669	6513	6482	6555	100	0.015
98	4284.1	4253.2	4226.0	3094	3074	3076	6675	6541	6508	6574	88	0.013
113	4284.5	4254.1	4225.3	3097	3079	3082	6688	6564	6532	6595	83	0.013
126	4283.4	4253.0	4224.1	3101	3082	3085	6704	6575	6543	6607	85	0.013
141	4281.2	4251.0	4223.3	3103	3086	3090	6709	6589	6563	6620	78	0.012
154	4281.5	4252.0	4224.4	3103	3086	3089	6709	6590	6560	6620	79	0.012
170	4282.0	4253.2	4226.2	3105	3088	3089	6719	6601	6563	6628	81	0.012
184	4281.8	4253.4	4226.1	3115	3080	3083	6762	6567	6538	6622	122	0.018
196	4281.5	4252.3	4225.8	3108	3080	3082	6731	6565	6533	6610	106	0.016
210	4280.0	4251.7	4224.1	3105	3078	3082	6716	6556	6530	6601	101	0.015
224	4283.1	4253.4	4227.3	3096	3079	3086	6682	6563	6552	6599	72	0.011
238	4284.8	4255.8	4228.5	3092	3083	3092	6667	6583	6579	6610	49	0.007
252	4285.3	4258.6	4230.2	3090	3082	3090	6659	6584	6574	6605	47	0.007
266	4285.7	4257.9	4231.2	3093	3084	3094	6673	6591	6592	6619	47	0.007
280	4286.3	4258.3	4231.9	3097	3087	3099	6691	6604	6615	6637	47	0.007
294	4285.9	4259.1	4232.5	3101	3088	3105	6708	6610	6641	6653	50	0.008
300	4285.0	4255.0	4230.0	3083	3088	3107	6629	6604	6646	6626	21	0.003

*i** means initial reading after 28 days of curing

Table A.3: Mass, frequency, and moduli of elasticity of Control-0.38 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4221.4	4270.1	4239.8	3071	3066	3078	6480	6533	6537	6517	32	0.005
17	4216.9	4265.2	4238.9	3000	3008	3016	6177	6281	6275	6244	59	0.009
28	4217.2	4267.9	4237.1	2965	2976	2985	6034	6152	6144	6110	66	0.011
43	4207.3	4265.8	4230.9	2933	2940	2947	5891	6001	5980	5957	59	0.010
56	4200.1	4254.2	4224.3	2914	2917	2919	5805	5891	5858	5851	44	0.007
70	4195.8	4246.0	4215.2	2898	2896	2893	5735	5796	5742	5757	33	0.006
85	4184.2	4240.3	4208.5	2871	2875	2871	5613	5704	5646	5654	46	0.008
98	4176.1	4233.4	4198.2	2845	2849	2850	5501	5592	5550	5548	46	0.008
113	4165.4	4229.0	4191.4	2822	2825	2834	5399	5493	5479	5457	51	0.009
126	4120.2	4181.5	4149.6	2810	2798	2805	5295	5328	5314	5312	17	0.003
141	4084.9	4143.5	4111.8	2800	2776	2783	5212	5197	5183	5197	15	0.003
154	4081.5	4125.4	4076.0	2785	2760	2780	5152	5115	5127	5131	19	0.004
170	4079.2	4109.0	4044.2	2774	2743	2776	5109	5032	5072	5071	39	0.008
184	4034.9	4082.2	4012.1	2758	2738	2760	4995	4981	4974	4983	11	0.002
196	4015.6	4050.3	3998.6	2746	2724	2739	4928	4891	4882	4901	24	0.005
210	3986.2	4004.7	3981.6	2740	2713	2727	4871	4797	4819	4829	38	0.008
224	3971.5	3982.5	3966.4	2724	2694	2713	4796	4704	4751	4751	46	0.010
238	3958.8	3961.7	3953.3	2707	2678	2697	4721	4624	4680	4675	49	0.010
252	3949.2	3948.1	3941.9	2699	2640	2684	4682	4478	4622	4594	105	0.023
266	3938.5	3930.5	3923.1	2690	2631	2674	4638	4428	4565	4544	107	0.023
280	3922.1	3909.7	3905.6	2674	2619	2663	4564	4365	4508	4479	103	0.023
294	3908.7	3889.4	3877.9	2667	2608	2653	4525	4306	4442	4424	111	0.025
300	3905.0	3885.0	3875.0	2665	2609	2655	4514	4304	4446	4421	107	0.024

*i** means initial reading after 28 days of curing

Table A.4: Mass, frequency, and moduli of elasticity of Control-0.38 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4208.0	4278.8	4291.5	3054	3093	3082	6388	6662	6634	6561	151	0.023
17	4185.3	4256.9	4269.0	3010	3054	3044	6171	6462	6438	6357	161	0.025
28	4184.8	4255.9	4267.9	3015	3062	3050	6191	6494	6462	6382	166	0.026
43	4186.0	4257.1	4269.4	3002	3052	3032	6140	6454	6388	6327	166	0.026
56	4188.5	4259.6	4272.5	2995	3043	3024	6115	6419	6359	6298	161	0.026
70	4191.2	4263.6	4276.6	2990	3036	3018	6098	6396	6340	6278	158	0.025
85	4197.5	4270.2	4282.0	2978	3024	3009	6059	6355	6310	6241	160	0.026
98	4206.4	4277.5	4289.1	2970	3013	2998	6039	6320	6274	6211	151	0.024
113	4208.0	4283.6	4295.2	2960	3005	2992	6000	6295	6258	6185	161	0.026
126	4211.4	4290.5	4304.6	2934	2981	2965	5900	6205	6159	6088	164	0.027
141	4218.5	4296.3	4307.7	2914	2960	2945	5830	6126	6081	6012	160	0.027
154	4223.1	4301.0	4310.4	2907	2948	2936	5808	6083	6047	5980	150	0.025
170	4226.4	4305.2	4315.6	2903	2939	2930	5797	6052	6030	5960	141	0.024
184	4226.8	4309.1	4316.4	2880	2912	2910	5706	5947	5949	5867	140	0.024
196	4231.5	4310.7	4316.8	2863	2901	2903	5645	5904	5921	5823	155	0.027
210	4233.8	4314.6	4318.5	2850	2888	2890	5597	5857	5870	5775	154	0.027
224	4238.5	4317.4	4321.6	2837	2875	2881	5552	5808	5838	5733	157	0.027
238	4243.7	4319.9	4328.1	2822	2863	2873	5500	5763	5814	5692	168	0.030
252	4249.1	4320.4	4329.3	2814	2857	2860	5476	5739	5763	5660	159	0.028
266	4243.2	4312.6	4324.1	2812	2856	2857	5461	5725	5744	5643	158	0.028
280	4237.9	4307.5	4317.8	2810	2854	2853	5446	5710	5720	5625	155	0.028
294	4231.0	4302.9	4314.1	2807	2851	2848	5426	5692	5695	5604	155	0.028
300	4230.0	4303.0	4320.0	2808	2851	2850	5428	5692	5711	5610	158	0.028

*i** means initial reading after 28 days of curing

Table A.5: Mass, frequency, and moduli of elasticity of 20% SL-0.38 specimens exposed to deionized water

	Mass of specimens (g)			**Frequency of specimens (Hz)**				**Moduli of elasticity of specimens (ksi)**					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4222.1	4201.7	4148.1	3058	3047	2990		6426	6349	6036	6270	207	0.033
16	4223.5	4202.9	4148.8	3043	3038	2983		6365	6313	6008	6229	193	0.031
30	4223.0	4201.9	4148.4	3055	3052	2994		6415	6370	6052	6279	198	0.031
43	4224.0	4203.7	4150.0	3070	3069	3008		6479	6444	6111	6345	203	0.032
56	4223.8	4203.6	4150.0	3074	3071	3010		6496	6452	6119	6356	206	0.032
70	4223.4	4203.3	4150.0	3075	3071	3010		6496	6452	6119	6356	206	0.032
84	4224.2	4205.1	4151.5	3082	3078	3019		6530	6484	6158	6391	203	0.032
99	4225.1	4206.0	4152.9	3091	3084	3028		6570	6511	6197	6426	200	0.031
112	4226.4	4206.4	4153.3	3097	3090	3036		6598	6537	6231	6455	197	0.030
126	4226.4	4207.1	4154.1	3107	3106	3044		6640	6606	6265	6503	208	0.032
140	4226.5	4207.9	4154.5	3120	3120	3050		6696	6667	6290	6551	226	0.035
154	4223.9	4204.3	4152.1	3115	3120	3048		6670	6661	6278	6536	224	0.034
170	4223.1	4205.1	4152.6	3114	3116	3051		6665	6645	6291	6534	210	0.032
183	4223.7	4203.7	4152.3	3112	3115	3055		6657	6639	6307	6534	197	0.030
196	4224.1	4204.5	4152.8	3114	3113	3057		6667	6631	6316	6538	193	0.029
210	4225.3	4205.1	4154.1	3114	3110	3057		6668	6619	6318	6535	190	0.029
224	4226.1	4205.8	4155.4	3115	3118	3060		6674	6655	6333	6554	192	0.029
238	4226.5	4206.4	4156.8	3117	3116	3066		6683	6647	6360	6563	177	0.027
252	4227.1	4206.9	4158.1	3119	3122	3063		6693	6674	6349	6572	193	0.029
266	4227.7	4207.8	4158.9	3123	3128	3067		6711	6701	6367	6593	196	0.030
280	4228.9	4208.6	4159.7	3122	3125	3070		6708	6689	6381	6593	184	0.028
294	4228.4	4209.0	4159.9	3125	3132	3072		6721	6720	6389	6610	191	0.029
300	4228.6	4209.4	4160.3	3124	3130	3074		6717	6712	6398	6609	182	0.028

*i** means initial reading after 28 days of curing

Table A.6: Mass, frequency, and moduli of elasticity of 20% SL-0.38 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4135.3	4181.5	4272.9	3004	3035	3081		6073	6269	6601	6314	267	0.042
16	4137.8	4184.2	4275.9	2975	3008	3055		5960	6162	6495	6206	270	0.044
30	4138.8	4184.9	4277.5	2992	3022	3074		6030	6220	6578	6276	278	0.044
43	4140.3	4186.3	4278.6	3002	3027	3076		6073	6243	6589	6301	263	0.042
56	4141.0	4187.1	4279.5	3005	3030	3081		6086	6256	6612	6318	268	0.042
70	4141.6	4188.3	4280.4	3006	3030	3084		6091	6258	6626	6325	274	0.043
84	4143.4	4189.6	4281.6	3014	3039	3090		6126	6297	6653	6359	269	0.042
99	4144.2	4191.0	4282.3	3021	3048	3097		6156	6337	6685	6392	269	0.042
112	4144.7	4191.4	4282.9	3025	3054	3099		6173	6362	6694	6410	264	0.041
126	4142.5	4189.0	4280.7	3031	3059	3107		6194	6380	6725	6433	270	0.042
140	4141.3	4188.1	4279.5	3035	3068	3116		6208	6416	6763	6462	280	0.043
154	4142.3	4189.3	4280.6	3032	3066	3114		6198	6409	6756	6454	282	0.044
170	4142.8	4190.2	4280.9	3033	3064	3111		6202	6402	6743	6449	273	0.042
183	4143.1	4189.6	4281.8	3033	3063	3110		6203	6397	6740	6447	272	0.042
196	4143.5	4189.2	4282.1	3032	3058	3108		6199	6376	6732	6436	271	0.042
210	4143.0	4189.4	4281.2	3030	3055	3105		6191	6364	6718	6424	269	0.042
224	4143.9	4190.8	4282.4	3033	3057	3107		6204	6374	6728	6435	267	0.042
238	4145.3	4192.1	4284.2	3036	3060	3109		6219	6389	6740	6449	266	0.041
252	4147.6	4195.7	4285.9	3039	3063	3112		6234	6407	6755	6465	265	0.041
266	4148.2	4194.9	4288.5	3038	3064	3115		6231	6410	6772	6471	276	0.043
280	4149.5	4195.7	4290.2	3041	3067	3113		6245	6423	6766	6478	265	0.041
294	4151.8	4196.2	4293.0	3044	3068	3116		6261	6428	6784	6491	267	0.041
300	4152.1	4196.5	4292.4	3042	3070	3114		6253	6437	6774	6488	264	0.041

*i** means initial reading after 28 days of curing

Table A.7: Mass, frequency, and moduli of elasticity of 20% SL-0.38 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4221.2	4195.0	4257.0	3022	3058	3035	6274	6385	6382	6347	63	0.010
16	4218.3	4190.0	4253.3	2993	3036	3007	6150	6286	6259	6232	72	0.012
30	4222.8	4192.5	4259.1	2986	3021	2993	6128	6227	6210	6188	53	0.009
43	4227.9	4198.4	4263.6	2976	3010	2982	6094	6191	6170	6152	51	0.008
56	4232.1	4201.6	4267.5	2964	2995	2971	6051	6134	6131	6105	47	0.008
70	4235.6	4207.1	4272.4	2955	2983	2963	6019	6093	6105	6072	46	0.008
84	4239.7	4213.5	4276.2	2946	2975	2951	5989	6069	6061	6040	44	0.007
99	4244.0	4218.2	4280.1	2934	2963	2940	5946	6027	6021	5998	45	0.008
112	4248.4	4221.2	4283.6	2927	2955	2933	5924	5999	5997	5973	43	0.007
126	4245.1	4220.4	4284.5	2923	2948	2928	5903	5969	5978	5950	41	0.007
140	4244.6	4219.8	4284.6	2915	2939	2921	5870	5932	5950	5917	42	0.007
154	4244.3	4220.0	4284.7	2902	2920	2910	5817	5856	5905	5860	44	0.008
170	4246.1	4221.3	4286.5	2897	2910	2900	5800	5818	5867	5828	35	0.006
183	4247.1	4222.7	4288.0	2888	2906	2889	5765	5804	5825	5798	30	0.005
196	4248.3	4223.3	4290.5	2880	2901	2883	5735	5785	5804	5774	36	0.006
210	4249.7	4223.1	4290.7	2875	2899	2880	5717	5776	5792	5762	40	0.007
224	4250.6	4224.8	4291.9	2869	2894	2871	5694	5759	5758	5737	37	0.006
238	4252.4	4226.3	4293.5	2864	2888	2874	5677	5737	5772	5729	48	0.008
252	4253.8	4228.2	4295.1	2859	2882	2866	5659	5716	5742	5705	42	0.007
266	4254.2	4227.9	4294.6	2855	2878	2858	5644	5699	5709	5684	35	0.006
280	4255.6	4230.1	4297.9	2851	2874	2853	5630	5687	5694	5670	35	0.006
294	4256.8	4231.9	4299.7	2845	2870	2848	5608	5673	5676	5652	39	0.007
300	4256.2	4231.5	4301.2	2847	2871	2846	5615	5677	5670	5654	34	0.006

*i** means initial reading after 28 days of curing

Table A.8: Mass, frequency, and moduli of elasticity of 20% SL-0.38 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4218.2	4186.6	4241.1	3061	3041	3036	6433	6301	6362	6365	66	0.010
16	4199.5	4167.1	4221.3	3015	3004	2992	6213	6120	6150	6161	47	0.008
30	4199.1	4166.4	4221.3	3006	2993	2985	6175	6074	6122	6124	51	0.008
43	4199.3	4166.6	4221.6	3013	2996	2990	6204	6087	6143	6145	59	0.010
56	4202.4	4171.6	4225.6	3010	2997	2993	6197	6098	6161	6152	50	0.008
70	4204.4	4174.4	4227.1	3012	2996	2995	6208	6098	6171	6159	56	0.009
84	4205.9	4176.1	4228.6	3016	3003	3001	6227	6129	6198	6185	50	0.008
99	4209.4	4177.6	4231.0	3020	3010	3006	6248	6160	6222	6210	45	0.007
112	4210.5	4178.2	4232.2	3022	3015	3009	6258	6181	6236	6225	40	0.006
126	4211.6	4179.6	4233.0	3024	3016	3008	6268	6188	6233	6230	40	0.006
140	4212.0	4180.1	4233.9	3030	3016	3008	6294	6188	6235	6239	53	0.008
154	4213.4	4181.5	4235.1	3022	3019	3005	6263	6203	6224	6230	30	0.005
170	4214.5	4182.9	4235.8	3019	3005	3000	6252	6147	6204	6201	52	0.008
183	4214.6	4183.8	4236.4	3013	2996	2997	6227	6112	6193	6177	59	0.010
196	4215.3	4183.5	4236.8	3008	3001	2993	6207	6132	6177	6172	38	0.006
210	4215.6	4184.1	4236.7	3005	3000	2987	6195	6129	6152	6159	34	0.005
224	4216.4	4185.9	4236.0	3003	2995	2985	6188	6111	6143	6147	39	0.006
238	4218.2	4187.4	4234.7	2999	2991	2981	6175	6097	6125	6132	39	0.006
252	4220.6	4189.1	4233.2	2995	2986	2977	6162	6079	6106	6115	42	0.007
266	4221.1	4190.3	4235.4	2994	2982	2975	6158	6064	6101	6108	47	0.008
280	4222.5	4191.7	4237.9	2992	2979	2972	6152	6054	6092	6099	49	0.008
294	4223.8	4192.0	4240.8	2990	2975	2970	6146	6038	6088	6091	54	0.009
300	4223.5	4192.4	4241.7	2989	2974	2969	6141	6035	6085	6087	53	0.009

*i** means initial reading after 28 days of curing

Table A.9: Mass, frequency, and moduli of elasticity of 35% SL-0.38 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4179.5	4231.5	4220.6	3049	3077	3075		6324	6520	6495	6446	107	0.017
16	4180.1	4232.4	4220.5	3030	3060	3062		6246	6450	6440	6379	115	0.018
28	4182.7	4234.5	4223.1	3042	3074	3077		6299	6512	6507	6440	122	0.019
43	4183.2	4235.1	4225.0	3055	3084	3090		6354	6556	6566	6492	119	0.018
56	4184.0	4236.2	4225.3	3064	3091	3102		6393	6587	6617	6532	122	0.019
70	4185.4	4237.5	4225.8	3071	3100	3109		6393	6587	6617	6532	122	0.019
84	4187.1	4238.0	4227.0	3079	3109	3114		6460	6667	6671	6599	120	0.018
99	4187.5	4238.4	4227.7	3083	3115	3120		6478	6693	6698	6623	126	0.019
112	4187.0	4238.3	4227.1	3085	3116	3122		6485	6698	6706	6630	125	0.019
127	4186.5	4237.6	4226.6	3088	3114	3121		6497	6688	6700	6629	114	0.017
140	4186.3	4237.1	4225.8	3091	3117	3125		6510	6700	6716	6642	115	0.017
154	4185.4	4236.5	4225.3	3093	3115	3124		6517	6690	6711	6639	107	0.016
168	4186.0	4237.4	4226.7	3096	3126	3130		6530	6739	6739	6670	121	0.018
182	4186.9	4237.1	4226.5	3098	3126	3129		6540	6739	6735	6671	114	0.017
196	4185.5	4236.7	4226.1	3102	3125	3130		6555	6734	6738	6676	105	0.016
210	4186.8	4236.4	4226.9	3105	3127	3133		6569	6742	6753	6688	103	0.015
225	4187.4	4237.8	4227.5	3108	3130	3137		6583	6757	6771	6704	105	0.016
238	4186.9	4238.4	4227.2	3110	3128	3139		6591	6749	6779	6706	101	0.015
253	4188.7	4239.8	4227.9	3109	3132	3141		6589	6769	6789	6716	110	0.016
266	4188.4	4240.7	4228.6	3111	3135	3145		6597	6783	6807	6729	115	0.017
280	4189.1	4241.8	4229.7	3112	3137	3144		6603	6794	6805	6734	113	0.017
294	4189.7	4241.5	4230.4	3114	3135	3147		6612	6785	6819	6738	111	0.016
300	4189.5	4241.2	4230.3	3114	3136	3148		6612	6788	6823	6741	113	0.017

*i** means initial reading after 28 days of curing

Table A.10: Mass, frequency, and moduli of elasticity of 35% SL-0.38 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4227.7	4220.1	4270.4	3064	3080	3070	6460	6516	6550	6509	46	0.007
16	4230.9	4223.4	4272.6	3048	3059	3053	6397	6432	6481	6437	42	0.007
28	4232.8	4224.6	4273.5	3054	3065	3060	6425	6459	6513	6466	44	0.007
43	4234.4	4225.8	4275.5	3067	3076	3069	6483	6507	6554	6515	36	0.006
56	4234.9	4227.5	4275.7	3077	3083	3077	6526	6540	6589	6551	33	0.005
70	4236.5	4229.6	4277.8	3080	3086	3081	6541	6556	6609	6568	36	0.005
84	4238.0	4231.5	4280.1	3082	3088	3087	6552	6567	6638	6586	46	0.007
99	4238.9	4231.8	4280.6	3083	3088	3091	6557	6568	6656	6594	54	0.008
112	4237.8	4231.4	4280.6	3084	3091	3090	6560	6580	6652	6597	48	0.007
127	4237.0	4231.0	4280.0	3086	3094	3092	6567	6592	6660	6606	48	0.007
140	4238.1	4230.7	4280.8	3089	3097	3089	6582	6604	6648	6611	34	0.005
154	4238.9	4230.9	4280.1	3090	3098	3087	6587	6609	6638	6611	26	0.004
168	4238.6	4231.4	4279.5	3085	3098	3094	6565	6610	6667	6614	51	0.008
182	4238.9	4232.1	4280.6	3087	3100	3103	6574	6619	6708	6634	68	0.010
196	4240.6	4231.8	4281.2	3088	3105	3110	6581	6640	6739	6654	80	0.012
210	4241.1	4232.3	4281.8	3090	3106	3112	6591	6645	6749	6662	80	0.012
225	4241.9	4233.7	4282.4	3093	3108	3115	6605	6656	6763	6674	81	0.012
238	4242.7	4235.2	4283.1	3094	3109	3114	6610	6663	6760	6677	76	0.011
253	4242.5	4236.4	4283.9	3096	3107	3116	6618	6656	6770	6681	79	0.012
266	4243.2	4236.8	4285.3	3097	3111	3117	6624	6674	6776	6691	78	0.012
280	4243.9	4237.1	4286.0	3099	3110	3112	6633	6670	6756	6686	63	0.009
294	4245.9	4238.0	4286.8	3098	3112	3119	6632	6680	6787	6700	79	0.012
300	4246.3	4237.9	4287.0	3097	3110	3118	6629	6671	6783	6694	80	0.012

*i** means initial reading after 28 days of curing

Table A.11: Mass, frequency, and moduli of elasticity of 35% SL-0.38 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4271.5	4310.0	4224.4	3105	2981	3087		6702	6233	6552	6496	239	0.037
16	4268.5	4306.8	4222.3	3065	2951	3049		6526	6104	6388	6340	215	0.034
28	4273.4	4311.4	4227.8	3075	2959	3060		6576	6144	6443	6388	222	0.035
43	4276.1	4314.2	4230.5	3077	2962	3060		6589	6160	6447	6399	218	0.034
56	4277.8	4316.1	4232.1	3077	2964	3059		6592	6171	6445	6403	213	0.033
70	4280.1	4318.4	4233.0	3078	2965	3060		6600	6179	6451	6410	213	0.033
84	4281.6	4320.0	4235.6	3078	2966	3059		6602	6185	6451	6413	211	0.033
99	4281.8	4320.9	4236.7	3079	2966	3059		6607	6186	6452	6415	212	0.033
112	4282.5	4321.2	4237.5	3077	2959	3051		6599	6158	6420	6392	222	0.035
127	4283.1	4322.5	4238.4	3074	2951	3045		6587	6126	6396	6370	231	0.036
140	4284.8	4324.3	4240.2	3068	2947	3039		6564	6112	6373	6350	227	0.036
154	4286.4	4325.6	4242.0	3060	2943	3036		6532	6098	6364	6331	219	0.035
168	4286.8	4326.8	4242.7	3058	2950	3037		6524	6128	6369	6340	200	0.031
182	4289.3	4328.6	4244.8	3056	2947	3034		6520	6118	6359	6332	202	0.032
196	4290.1	4330.3	4245.7	3057	2943	3033		6525	6104	6357	6329	212	0.033
210	4292.4	4331.8	4246.5	3055	2941	3031		6520	6098	6349	6322	212	0.034
225	4293.8	4332.4	4247.3	3052	2939	3029		6509	6091	6342	6314	211	0.033
238	4294.2	4333.2	4248.6	3053	2935	3027		6514	6075	6336	6308	221	0.035
253	4296.1	4333.9	4250.0	3051	2936	3025		6509	6080	6329	6306	215	0.034
266	4296.8	4334.6	4252.3	3049	2933	3022		6501	6069	6320	6297	217	0.034
280	4298.0	4336.3	4254.9	3046	2930	3020		6490	6059	6316	6288	217	0.035
294	4299.5	4338.9	4255.8	3047	2928	3018		6497	6054	6309	6287	222	0.035
300	4300.0	4339.7	4255.4	3048	2930	3018		6502	6063	6308	6291	220	0.035

*i** means initial reading after 28 days of curing

Table A.12: Mass, frequency, and moduli of elasticity of 35% SL-0.38 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4211.8	4190.3	4238.5	3083	3043	3077	6515	6315	6531	6454	121	0.019
16	4196.0	4176.3	4222.7	3028	2994	3019	6261	6093	6264	6206	98	0.016
28	4196.3	4176.6	4224.1	3044	3014	3035	6328	6175	6333	6279	90	0.014
43	4200.6	4180.8	4227.1	3045	3010	3041	6339	6165	6362	6289	108	0.017
56	4202.3	4181.4	4228.0	3044	3010	3044	6337	6166	6376	6293	112	0.018
70	4202.9	4181.8	4229.4	3047	3014	3047	6351	6183	6391	6308	110	0.018
84	4203.1	4183.5	4231.8	3050	3019	3050	6364	6206	6407	6325	106	0.017
99	4203.7	4183.1	4231.5	3050	3021	3051	6364	6213	6411	6329	103	0.016
112	4203.1	4183.8	4231.8	3053	3019	3050	6376	6206	6407	6330	108	0.017
127	4203.5	4184.2	4232.1	3057	3015	3049	6393	6190	6403	6329	120	0.019
140	4204.1	4184.8	4232.5	3061	3017	3053	6411	6199	6421	6344	125	0.020
154	4204.5	4184.5	4232.0	3063	3014	3052	6420	6187	6416	6341	133	0.021
168	4205.9	4186.1	4233.0	3040	3009	3040	6326	6169	6367	6287	105	0.017
182	4206.3	4186.8	4233.9	3041	3011	3046	6331	6178	6393	6301	111	0.018
196	4206.0	4186.3	4233.5	3043	3011	3048	6339	6177	6401	6306	116	0.018
210	4205.8	4186.5	4233.8	3041	3010	3045	6330	6173	6389	6297	112	0.018
225	4206.1	4186.9	4234.1	3039	3008	3046	6322	6166	6394	6294	117	0.019
238	4206.7	4187.1	4234.3	3035	3007	3043	6306	6162	6381	6283	112	0.018
253	4206.4	4187.8	4234.7	3037	3005	3040	6314	6155	6369	6279	112	0.018
266	4206.8	4187.5	4234.5	3034	3003	3037	6302	6146	6357	6268	109	0.017
280	4206.3	4187.6	4234.9	3031	3000	3035	6289	6134	6349	6257	111	0.018
294	4206.7	4187.4	4235.3	3033	2997	3032	6298	6121	6337	6252	115	0.018
300	4206.9	4187.5	4235.5	3032	2998	3031	6294	6126	6333	6251	110	0.018

*i** means initial reading after 28 days of curing

Table A.13: Mass, frequency, and moduli of elasticity of 50% SL-0.38 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4176.4	4183.3	4168.7	3032	3014	3008		6249	6185	6139	6191	55	0.009
15	4177.9	4184.4	4170.8	3016	2994	2992		6185	6105	6077	6122	56	0.009
28	4182.0	4188.1	4174.6	3031	3010	3005		6253	6176	6135	6188	60	0.010
43	4182.4	4188.6	4175.1	3037	3017	3011		6278	6205	6160	6215	59	0.010
56	4183.5	4189.2	4175.8	3043	3024	3019		6305	6235	6194	6245	56	0.009
70	4184.2	4189.2	4176.4	3049	3031	3027		6305	6235	6194	6245	56	0.009
84	4185.1	4190.5	4177.1	3055	3038	3033		6357	6295	6254	6302	52	0.008
98	4185.9	4192.2	4178.3	3065	3046	3043		6400	6330	6297	6342	53	0.008
113	4186.4	4193.6	4179.2	3071	3052	3052		6426	6357	6336	6373	47	0.007
126	4185.2	4192.3	4177.5	3077	3056	3060		6449	6372	6366	6396	46	0.007
142	4183.6	4190.3	4177.1	3086	3064	3066		6484	6402	6391	6426	51	0.008
154	4184.8	4190.1	4177.8	3085	3067	3065		6482	6415	6388	6428	49	0.008
169	4184.4	4190.5	4178.1	3086	3068	3063		6486	6420	6380	6428	54	0.008
182	4184.5	4190.5	4178.0	3088	3071	3067		6494	6432	6396	6441	50	0.008
196	4184.9	4190.3	4177.7	3090	3074	3071		6503	6444	6412	6453	46	0.007
210	4184.1	4190.1	4177.8	3091	3077	3074		6506	6457	6425	6463	41	0.006
225	4184.9	4191.3	4179.8	3093	3078	3077		6516	6463	6441	6473	39	0.006
238	4185.6	4192.5	4181.5	3094	3080	3078		6521	6473	6448	6481	37	0.006
253	4186.4	4195.5	4184.3	3096	3083	3079		6531	6490	6456	6492	37	0.006
265	4187.5	4193.9	4186.7	3095	3081	3082		6528	6479	6472	6493	31	0.005
280	4188.9	4196.8	4189.4	3097	3084	3086		6539	6496	6493	6510	25	0.004
294	4190.1	4199.0	4193.9	3100	3085	3084		6554	6504	6492	6516	33	0.005
300	4190.5	4199.7	4194.7	3099	3085	3085		6550	6505	6497	6517	28	0.004

*i** means initial reading after 28 days of curing

Table A.14: Mass, frequency, and moduli of elasticity of 50% SL-0.38 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4175.0	4171.7	4092.8	3014	3032	2978	6173	6242	5907	6107	176	0.029
15	4177.7	4174.8	4094.4	2996	3024	2961	6103	6213	5842	6053	190	0.031
28	4178.0	4165.4	4093.4	2997	3031	2970	6108	6228	5877	6071	179	0.029
43	4178.8	4166.2	4094.2	3003	3035	2976	6133	6246	5901	6093	176	0.029
56	4179.6	4167.2	4095.0	3008	3040	2981	6155	6268	5922	6115	176	0.029
70	4180.4	4168.3	4096.3	3013	3044	2987	6177	6286	5948	6137	172	0.028
84	4181.2	4169.5	4097.6	3019	3049	2992	6202	6308	5970	6160	173	0.028
98	4182.0	4170.2	4098.5	3026	3053	2998	6232	6326	5995	6185	170	0.028
113	4183.1	4171.0	4099.8	3032	3056	3005	6259	6340	6025	6208	163	0.026
126	4185.1	4172.6	4102.3	3033	3054	2999	6266	6334	6005	6202	174	0.028
142	4186.1	4173.0	4103.2	3032	3051	2995	6263	6322	5990	6192	177	0.029
154	4186.2	4173.4	4103.5	3030	3057	2997	6255	6348	5999	6200	181	0.029
169	4185.9	4173.0	4102.9	3030	3060	3003	6255	6359	6022	6212	173	0.028
182	4185.7	4173.2	4102.8	3034	3063	3007	6271	6372	6038	6227	172	0.028
196	4185.6	4173.5	4103.5	3038	3067	3011	6287	6389	6055	6244	171	0.027
210	4185.8	4173.0	4103.3	3040	3070	3014	6296	6401	6067	6254	171	0.027
225	4187.2	4173.9	4104.0	3042	3070	3015	6306	6402	6072	6260	170	0.027
238	4188.6	4175.4	4104.9	3045	3071	3017	6321	6409	6081	6270	170	0.027
253	4188.0	4177.2	4105.3	3044	3074	3018	6316	6424	6086	6275	173	0.028
265	4189.6	4177.9	4106.8	3045	3075	3020	6322	6429	6096	6283	170	0.027
280	4190.9	4178.5	4108.7	3046	3077	3022	6328	6439	6107	6291	169	0.027
294	4192.8	4179.6	4109.9	3048	3079	3025	6340	6449	6121	6303	167	0.026
300	4193.2	4179.8	4110.2	3047	3080	3026	6336	6453	6125	6305	166	0.026

*i** means initial reading after 28 days of curing

Table A.15: Mass, frequency, and moduli of elasticity of 50% SL-0.38 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4105.8	4159.3	4155.4	2986	3025	2988	5958	6194	6038	6064	120	0.020
15	4106.1	4160.1	4155.2	2952	2985	2958	5824	6033	5917	5925	105	0.018
28	4109.2	4163.6	4158.4	2965	2998	2970	5879	6091	5970	5980	106	0.018
43	4110.1	4164.5	4159.1	2967	3000	2973	5889	6100	5983	5991	106	0.018
56	4111.0	4165.1	4160.0	2970	3002	2976	5902	6109	5996	6002	104	0.017
70	4111.7	4166.0	4160.9	2971	3004	2978	5907	6119	6006	6010	106	0.018
84	4112.6	4167.1	4161.8	2973	3006	2981	5916	6128	6019	6021	106	0.018
98	4113.8	4167.9	4162.7	2974	3007	2983	5922	6134	6028	6028	106	0.018
113	4114.7	4168.8	4163.5	2975	3008	2986	5927	6139	6042	6036	106	0.018
126	4115.4	4170.1	4165.7	2971	3005	2981	5912	6129	6025	6022	108	0.018
142	4116.8	4170.6	4166.4	2965	3000	2975	5890	6109	6002	6000	109	0.018
154	4116.3	4171.1	4166.1	2970	3002	2979	5909	6118	6017	6015	104	0.017
169	4115.8	4170.8	4166.0	2972	3003	2980	5917	6121	6021	6020	102	0.017
182	4115.9	4170.5	4165.8	2974	3003	2978	5925	6121	6013	6020	98	0.016
196	4116.1	4171.1	4165.2	2973	3004	2977	5921	6126	6008	6018	103	0.017
210	4116.3	4170.7	4165.4	2974	3002	2974	5925	6117	5996	6013	97	0.016
225	4116.6	4170.5	4166.2	2972	2999	2972	5918	6105	5989	6004	94	0.016
238	4117.2	4171.3	4167.4	2969	2996	2973	5907	6094	5995	5998	94	0.016
253	4119.6	4173.6	4167.9	2967	2994	2975	5902	6089	6004	5998	93	0.016
265	4120.5	4175.8	4169.5	2968	2997	2971	5908	6104	5990	6001	99	0.016
280	4121.8	4177.1	4171.7	2964	2993	2969	5893	6090	5985	5989	98	0.016
294	4123.4	4178.5	4173.2	2966	2988	2966	5904	6072	5975	5983	84	0.014
300	4123.7	4178.4	4173.9	2965	2990	2968	5900	6080	5984	5988	90	0.015

*i** means initial reading after 28 days of curing

Table A.16: Mass, frequency, and moduli of elasticity of 50% SL-0.38 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4135.1	4242.3	4081.7	2974	3002	2960	5952	6222	5820	5998	205	0.034
15	4123.5	4230.7	4068.5	2925	2952	2911	5742	6000	5611	5784	198	0.034
28	4124.3	4231.7	4069.8	2934	2964	2927	5778	6051	5675	5835	194	0.033
43	4125.0	4232.4	4070.4	2937	2969	2930	5791	6072	5687	5850	199	0.034
56	4125.8	4233.2	4071.2	2941	2975	2933	5808	6098	5700	5869	206	0.035
70	4126.6	4233.8	4072.0	2945	2979	2935	5825	6115	5709	5883	209	0.036
84	4127.4	4234.6	4072.8	2948	2984	2937	5838	6137	5718	5897	216	0.037
98	4128.3	4235.2	4073.4	2951	2989	2940	5851	6158	5730	5913	221	0.037
113	4129.0	4236.4	4073.8	2955	2992	2943	5868	6172	5743	5928	221	0.037
126	4129.3	4237.2	4074.1	2951	2987	2934	5853	6153	5708	5904	227	0.038
142	4128.9	4236.9	4073.7	2949	2981	2927	5844	6128	5680	5884	226	0.038
154	4129.6	4237.8	4074.1	2948	2982	2931	5841	6133	5696	5890	223	0.038
169	4130.0	4237.5	4074.4	2945	2982	2933	5830	6133	5704	5889	220	0.037
182	4129.5	4237.8	4075.0	2947	2985	2936	5837	6145	5717	5900	221	0.037
196	4129.8	4237.0	4074.8	2949	2983	2934	5845	6136	5709	5897	218	0.037
210	4130.2	4237.2	4075.1	2950	2985	2935	5850	6145	5713	5903	220	0.037
225	4130.5	4237.5	4075.8	2948	2982	2937	5842	6133	5722	5899	211	0.036
238	4129.7	4237.8	4075.2	2950	2984	2934	5849	6141	5709	5900	220	0.037
253	4130.2	4238.0	4074.4	2949	2981	2931	5846	6129	5697	5891	220	0.037
265	4130.7	4238.5	4074.9	2946	2978	2929	5835	6118	5690	5881	218	0.037
280	4130.6	4237.9	4075.9	2947	2979	2930	5838	6121	5695	5885	217	0.037
294	4130.3	4239.1	4075.0	2951	2975	2928	5854	6106	5686	5882	212	0.036
300	4130.5	4238.8	4075.3	2947	2974	2926	5838	6102	5679	5873	214	0.036

*i** means initial reading after 28 days of curing

Table A.17: Mass, frequency, and moduli of elasticity of 20% FA-0.38 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4199.6	4225.3	4193.3	2993	3033	3041	6123	6326	6311	6253	113	0.018
16	4197.7	4222.1	4190.3	2973	3021	3029	6038	6271	6257	6189	130	0.021
28	4200.8	4224.1	4192.5	2993	3037	3046	6125	6341	6331	6265	122	0.019
44	4203.1	4225.3	4194.1	3002	3044	3053	6165	6372	6362	6300	117	0.019
56	4204.9	4227.0	4195.8	3010	3051	3061	6200	6404	6398	6334	116	0.018
70	4205.1	4227.9	4197.3	3018	3060	3068	6200	6404	6398	6334	116	0.018
84	4206.8	4228.6	4200.4	3027	3067	3077	6273	6474	6473	6407	115	0.018
99	4207.3	4230.4	4201.8	3037	3075	3086	6316	6510	6513	6446	113	0.018
112	4208.6	4232.0	4202.1	3049	3080	3094	6368	6534	6547	6483	100	0.015
126	4209.0	4232.5	4202.3	3046	3086	3096	6356	6560	6556	6491	117	0.018
141	4209.1	4232.8	4201.8	3047	3091	3097	6360	6582	6559	6500	122	0.019
155	4209.5	4232.3	4201.3	3044	3095	3102	6348	6598	6580	6509	139	0.021
168	4208.9	4232.3	4201.5	3046	3096	3104	6356	6602	6588	6515	139	0.021
182	4209.5	4233.1	4201.9	3049	3100	3106	6369	6621	6597	6529	139	0.021
196	4210.1	4233.5	4202.3	3052	3103	3109	6382	6634	6611	6542	139	0.021
210	4210.4	4234.0	4202.8	3055	3107	3112	6395	6652	6624	6557	141	0.021
224	4210.7	4234.2	4203.3	3058	3105	3115	6408	6644	6638	6563	134	0.020
238	4211.3	4234.9	4203.7	3061	3109	3118	6422	6662	6651	6578	136	0.021
252	4210.9	4234.7	4204.1	3064	3112	3121	6434	6675	6665	6591	136	0.021
266	4211.2	4234.9	4204.8	3067	3115	3119	6447	6688	6657	6597	131	0.020
280	4211.7	4234.5	4204.3	3072	3118	3120	6469	6700	6661	6610	124	0.019
294	4212.2	4235.1	4204.9	3076	3117	3123	6486	6697	6675	6619	116	0.017
300	4212.9	4235.8	4205.1	3075	3119	3124	6483	6706	6679	6623	122	0.018

*i** means initial reading after 28 days of curing

Table A.18: Mass, frequency, and moduli of elasticity of 20% FA-0.38 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4204.7	4235.4	4130.3	3058	3074	3024	6399	6514	6147	6353	188	0.030
16	4202.2	4233.6	4127.7	3031	3042	2991	6283	6376	6010	6223	190	0.031
28	4204.1	4234.9	4130.0	3043	3052	3005	6336	6420	6070	6275	183	0.029
44	4205.3	4234.5	4131.2	3050	3059	3011	6367	6449	6096	6304	185	0.029
56	4207.4	4235.8	4132.5	3058	3066	3017	6403	6480	6122	6335	189	0.030
70	4207.1	4236.4	4132.7	3063	3072	3024	6424	6507	6151	6360	186	0.029
84	4208.9	4238.3	4135.6	3069	3079	3030	6452	6539	6179	6390	188	0.029
99	4210.1	4239.1	4136.1	3074	3084	3035	6475	6562	6201	6412	189	0.029
112	4210.7	4239.3	4135.9	3076	3088	3039	6484	6579	6217	6427	188	0.029
126	4211.1	4239.0	4136.7	3079	3089	3040	6497	6583	6222	6434	189	0.029
141	4211.5	4240.4	4136.1	3078	3088	3039	6494	6581	6217	6431	190	0.030
155	4211.0	4239.2	4136.3	3080	3087	3041	6501	6575	6225	6434	184	0.029
168	4211.6	4239.7	4137.2	3083	3092	3041	6515	6597	6227	6446	194	0.030
182	4212.3	4240.8	4137.3	3084	3090	3044	6520	6590	6239	6450	186	0.029
196	4213.2	4241.1	4138.0	3085	3089	3046	6526	6586	6249	6454	180	0.028
210	4213.8	4242.5	4138.7	3087	3091	3048	6535	6597	6258	6463	181	0.028
224	4214.5	4242.9	4139.3	3088	3093	3050	6541	6606	6267	6471	180	0.028
238	4215.2	4243.4	4140.5	3090	3094	3052	6550	6611	6277	6479	178	0.027
252	4216.0	4244.6	4141.7	3089	3092	3049	6547	6605	6266	6473	181	0.028
266	4217.3	4245.1	4142.3	3091	3097	3053	6558	6627	6284	6489	181	0.028
280	4217.9	4246.3	4143.8	3092	3099	3055	6563	6637	6294	6498	180	0.028
294	4218.8	4247.0	4144.4	3094	3104	3057	6573	6660	6303	6512	186	0.029
300	4219.2	4247.1	4144.2	3093	3101	3056	6569	6647	6299	6505	183	0.028

*i** means initial reading after 28 days of curing

Table A.19: Mass, frequency, and moduli of elasticity of 20% FA-0.38 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3		1	2	3	Average	Std Dev	COV
*i**	4123.6	4221.9	4162.0	3015	3019	3032		6101	6263	6227	6197	85	0.014
16	4110.5	4210.7	4148.5	2960	2965	2983		5861	6025	6008	5965	90	0.015
28	4114.4	4214.4	4153.5	2950	2964	2980		5827	6026	6003	5952	109	0.018
44	4119.1	4218.5	4156.8	2944	2959	2974		5810	6011	5984	5935	109	0.018
56	4124.6	4222.8	4160.1	2937	2951	2969		5791	5985	5968	5915	108	0.018
70	4131.6	4226.7	4164.3	2930	2946	2962		5773	5970	5946	5896	108	0.018
84	4135.4	4230.5	4169.5	2925	2939	2958		5758	5947	5938	5881	106	0.018
99	4137.0	4233.4	4172.4	2919	2935	2953		5737	5935	5922	5865	111	0.019
112	4137.1	4235.6	4176.6	2913	2933	2949		5714	5930	5912	5852	120	0.021
126	4138.8	4237.1	4177.3	2908	2926	2942		5696	5904	5884	5828	115	0.020
141	4141.3	4239.5	4179.2	2903	2919	2937		5680	5879	5867	5809	112	0.019
155	4143.1	4241.7	4180.6	2899	2915	2930		5667	5866	5841	5791	108	0.019
168	4145.5	4243.7	4183.1	2899	2911	2933		5670	5853	5857	5793	107	0.018
182	4147.5	4245.8	4183.7	2891	2907	2925		5642	5840	5826	5769	110	0.019
196	4148.2	4247.3	4185.1	2887	2902	2920		5627	5821	5808	5752	108	0.019
210	4149.6	4249.4	4187.3	2882	2899	2922		5609	5812	5819	5747	119	0.021
224	4150.9	4250.2	4189.1	2877	2894	2917		5592	5793	5801	5729	119	0.021
238	4152.2	4252.4	4191.7	2873	2897	2913		5578	5808	5789	5725	128	0.022
252	4153.7	4253.6	4193.3	2871	2893	2909		5572	5794	5775	5714	123	0.022
266	4155.4	4254.8	4195.9	2868	2890	2907		5563	5784	5771	5706	124	0.022
280	4157.7	4255.3	4197.2	2864	2886	2905		5550	5768	5765	5694	125	0.022
294	4159.8	4256.2	4199.1	2863	2887	2902		5549	5774	5755	5693	125	0.022
300	4160.2	4256.3	4199.3	2862	2885	2901		5546	5766	5752	5688	123	0.022

*i** means initial reading after 28 days of curing

Table A.20: Mass, frequency, and moduli of elasticity of 20% FA-0.38 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4156.1	4176.8	4143.0	2996	3022	3006	6072	6208	6093	6124	73	0.012
16	4125.9	4146.6	4113.0	2930	2953	2937	5765	5885	5774	5808	67	0.012
28	4126.0	4146.0	4112.3	2937	2956	2940	5792	5896	5785	5825	62	0.011
44	4127.5	4147.2	4113.5	2940	2958	2943	5806	5906	5799	5837	60	0.010
56	4128.9	4148.8	4114.8	2943	2961	2945	5820	5920	5808	5850	61	0.010
70	4129.4	4150.0	4116.5	2946	2963	2948	5833	5930	5823	5862	59	0.010
84	4130.1	4151.6	4118.0	2949	2966	2953	5846	5944	5844	5878	57	0.010
99	4132.4	4153.8	4119.5	2947	2969	2956	5841	5959	5858	5886	64	0.011
112	4133.1	4153.5	4119.3	2950	2972	2960	5854	5971	5874	5900	63	0.011
126	4133.8	4154.1	4119.5	2952	2974	2963	5863	5980	5886	5910	62	0.010
141	4134.5	4154.0	4121.1	2954	2975	2966	5872	5984	5900	5919	58	0.010
155	4134.0	4154.2	4120.6	2954	2976	2966	5871	5988	5900	5920	61	0.010
168	4134.2	4154.0	4120.3	2946	2970	2957	5840	5964	5864	5889	66	0.011
182	4135.2	4155.4	4121.8	2952	2973	2963	5865	5978	5889	5911	59	0.010
196	4135.9	4156.0	4122.3	2950	2970	2961	5858	5966	5882	5902	57	0.010
210	4136.4	4156.7	4122.8	2948	2971	2960	5851	5971	5879	5900	63	0.011
224	4136.8	4157.1	4123.7	2946	2970	2959	5843	5968	5876	5896	65	0.011
238	4138.2	4157.7	4123.4	2947	2969	2957	5849	5965	5868	5894	62	0.011
252	4137.7	4158.6	4124.5	2945	2968	2958	5841	5962	5873	5892	63	0.011
266	4138.3	4159.2	4124.1	2943	2965	2956	5834	5951	5865	5883	61	0.010
280	4138.9	4159.5	4124.9	2944	2966	2953	5838	5955	5854	5883	64	0.011
294	4139.5	4158.9	4125.2	2942	2964	2951	5831	5947	5847	5875	63	0.011
300	4138.3	4159.0	4125.7	2943	2966	2949	5834	5955	5839	5876	68	0.012

*i** means initial reading after 28 days of curing

Table A.21: Mass, frequency, and moduli of elasticity of 35% FA-0.38 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4165.2	4147.9	4126.2	2999	2998	2982		6097	6068	5972	6045	66	0.011
14	4160.0	4141.6	4120.8	2990	2999	2981		6053	6062	5960	6025	57	0.009
28	4162.1	4142.5	4122.4	3001	3008	2993		6101	6100	6010	6070	52	0.009
43	4164.3	4145.2	4124.2	3012	3019	3002		6149	6149	6049	6116	58	0.009
56	4163.9	4147.6	4125.9	3024	3030	3013		6197	6197	6096	6164	58	0.009
71	4165.2	4146.8	4126.7	3035	3042	3024		6197	6197	6096	6164	58	0.009
84	4166.3	4148.2	4125.4	3046	3055	3035		6291	6301	6185	6259	65	0.010
98	4168.4	4149.6	4128.3	3060	3067	3046		6352	6353	6234	6313	69	0.011
113	4168.1	4149.7	4129.0	3070	3075	3053		6394	6386	6264	6348	73	0.011
126	4168.4	4151.3	4130.5	3069	3077	3056		6390	6397	6278	6355	67	0.010
142	4169.8	4152.4	4130.3	3070	3077	3058		6396	6399	6286	6360	64	0.010
155	4169.1	4151.8	4130.5	3069	3080	3060		6391	6410	6295	6365	62	0.010
168	4169.7	4151.3	4130.8	3069	3082	3060		6392	6418	6295	6368	65	0.010
182	4170.1	4151.9	4130.7	3072	3085	3063		6405	6431	6307	6381	65	0.010
196	4171.7	4152.3	4132.1	3076	3090	3065		6424	6453	6318	6398	71	0.011
210	4171.3	4153.1	4131.8	3081	3087	3069		6444	6441	6334	6406	63	0.010
224	4172.6	4152.8	4132.4	3085	3092	3073		6463	6462	6351	6425	64	0.010
238	4172.9	4153.4	4133.2	3090	3093	3070		6485	6467	6340	6430	79	0.012
252	4173.2	4153.9	4133.6	3089	3096	3075		6481	6480	6361	6441	69	0.011
266	4173.8	4154.4	4134.1	3095	3097	3074		6507	6485	6358	6450	80	0.012
280	4174.3	4154.8	4134.8	3099	3095	3077		6525	6477	6371	6458	78	0.012
294	4174.0	4154.1	4134.9	3107	3100	3082		6558	6497	6392	6482	84	0.013
300	4173.7	4154.3	4134.6	3105	3099	3080		6549	6493	6384	6475	84	0.013

*i** means initial reading after 28 days of curing

Table A.22: Mass, frequency, and moduli of elasticity of 35% FA-0.38 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4138.1	4134.2	4079.1	3003	2980	2952	6073	5975	5785	5945	147	0.025
14	4134.2	4129.4	4074.4	2988	2970	2940	6007	5928	5732	5889	142	0.024
28	4134.8	4130.5	4075.1	2994	2977	2948	6032	5958	5764	5918	139	0.023
43	4136.5	4132.4	4076.8	3000	2984	2955	6059	5989	5794	5947	137	0.023
56	4138.8	4133.8	4078.0	3006	2991	2963	6087	6019	5827	5977	135	0.023
71	4137.4	4135.1	4080.1	3011	2999	2971	6105	6053	5861	6006	128	0.021
84	4139.5	4136.8	4079.3	3016	3009	2980	6128	6096	5896	6040	126	0.021
98	4140.7	4136.4	4081.3	3020	3018	2986	6146	6132	5922	6067	125	0.021
113	4142.5	4137.0	4082.7	3024	3027	2993	6165	6169	5952	6096	124	0.020
126	4144.2	4138.4	4083.9	3030	3025	2990	6192	6163	5942	6099	137	0.022
142	4144.3	4140.5	4085.4	3035	3021	2986	6213	6150	5928	6097	149	0.025
155	4145.3	4141.8	4086.1	3032	3020	2989	6202	6148	5941	6097	138	0.023
168	4145.5	4141.6	4086.3	3031	3020	2991	6198	6148	5950	6099	131	0.022
182	4145.9	4141.9	4086.8	3033	3022	2993	6207	6156	5958	6107	131	0.022
196	4146.4	4142.4	4087.3	3036	3025	2995	6220	6169	5967	6119	134	0.022
210	4146.7	4142.8	4088.1	3034	3026	2998	6212	6174	5980	6122	124	0.020
224	4147.9	4143.6	4087.9	3038	3029	3000	6231	6187	5988	6135	129	0.021
238	4147.3	4144.4	4088.4	3040	3035	3003	6238	6213	6001	6151	130	0.021
252	4148.7	4145.7	4090.2	3041	3032	3005	6244	6203	6011	6153	124	0.020
266	4149.2	4145.2	4089.5	3039	3036	3002	6237	6218	5998	6151	133	0.022
280	4150.8	4146.7	4091.2	3042	3038	3007	6251	6229	6021	6167	127	0.021
294	4152.1	4147.3	4091.9	3045	3040	3011	6266	6238	6038	6180	124	0.020
300	4151.8	4147.8	4092.3	3043	3041	3009	6257	6243	6030	6177	127	0.021

*i** means initial reading after 28 days of curing

Table A.23: Mass, frequency, and moduli of elasticity of 35% FA-0.38 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4129.1	4116.4	4167.1	2983	2943	2985	5980	5803	6043	5942	125	0.021
14	4117.7	4105.5	4155.6	2933	2896	2943	5765	5604	5858	5742	129	0.022
28	4119.2	4106.8	4158.2	2935	2899	2945	5775	5617	5870	5754	127	0.022
43	4121.5	4108.7	4161.1	2934	2900	2949	5774	5624	5890	5763	133	0.023
56	4123.9	4107.4	4163.4	2936	2904	2952	5786	5638	5905	5776	134	0.023
71	4126.7	4113.5	4166.7	2938	2901	2957	5797	5634	5930	5787	148	0.026
84	4129.0	4117.1	4170.3	2937	2905	2956	5797	5655	5931	5794	138	0.024
98	4132.4	4116.3	4173.1	2936	2907	2960	5798	5661	5951	5803	145	0.025
113	4134.9	4119.3	4172.2	2937	2909	2963	5805	5673	5961	5813	144	0.025
126	4137.8	4122.1	4175.1	2934	2906	2957	5797	5665	5942	5801	138	0.024
142	4139.1	4124.1	4177.2	2930	2902	2950	5783	5653	5916	5784	132	0.023
155	4139.8	4125.3	4179.2	2928	2899	2949	5776	5643	5915	5778	136	0.024
168	4141.6	4126.8	4180.2	2925	2895	2947	5767	5629	5909	5768	140	0.024
182	4143.5	4126.1	4180.9	2927	2893	2950	5777	5620	5922	5773	151	0.026
196	4144.2	4128.3	4182.5	2929	2890	2946	5786	5612	5908	5769	149	0.026
210	4146.8	4130.1	4185.1	2925	2891	2944	5774	5618	5903	5765	143	0.025
224	4149.2	4131.6	4184.4	2928	2896	2941	5789	5640	5890	5773	126	0.022
238	4152.3	4134.2	4186.3	2931	2893	2943	5806	5631	5901	5779	137	0.024
252	4153.8	4133.9	4188.5	2930	2890	2938	5804	5619	5884	5769	136	0.024
266	4154.2	4136.1	4190.1	2932	2889	2935	5812	5618	5874	5768	134	0.023
280	4156.1	4138.5	4192.9	2928	2885	2937	5799	5606	5886	5764	143	0.025
294	4155.7	4139.9	4194.1	2922	2887	2932	5775	5616	5868	5753	128	0.022
300	4156.3	4140.4	4194.3	2919	2884	2928	5764	5605	5852	5740	125	0.022

*i** means initial reading after 28 days of curing

Table A.24: Mass, frequency, and moduli of elasticity of 35% FA-0.38 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			**Frequency of specimens (Hz)**			**Moduli of elasticity of specimens (ksi)**					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4151.9	4133.1	4132.0	3005	2982	2953	6102	5982	5864	5983	119	0.020
14	4116.8	4099.5	4098.6	2920	2897	2869	5713	5600	5491	5601	111	0.020
28	4117.2	4100.2	4099.1	2924	2901	2873	5729	5616	5507	5617	111	0.020
43	4116.9	4101.5	4100.4	2928	2905	2878	5744	5633	5528	5635	108	0.019
56	4118.6	4101.2	4102.7	2933	2911	2883	5766	5656	5550	5657	108	0.019
71	4119.5	4100.9	4103.9	2937	2916	2889	5783	5675	5575	5678	104	0.018
84	4120.4	4102.4	4102.1	2938	2920	2893	5789	5693	5588	5690	100	0.018
98	4120.9	4103.1	4103.0	2940	2924	2896	5797	5709	5600	5702	99	0.017
113	4121.4	4102.9	4103.6	2942	2927	2898	5806	5721	5609	5712	99	0.017
126	4121.0	4103.2	4104.5	2942	2927	2896	5805	5721	5603	5710	102	0.018
142	4121.9	4104.4	4104.8	2941	2926	2892	5802	5719	5587	5703	108	0.019
155	4121.5	4103.9	4104.1	2938	2925	2895	5790	5714	5598	5701	97	0.017
168	4121.3	4102.9	4104.3	2937	2926	2900	5786	5717	5618	5707	85	0.015
182	4121.0	4103.2	4104.2	2933	2928	2897	5770	5725	5606	5700	85	0.015
196	4120.6	4103.9	4104.6	2935	2924	2893	5777	5711	5591	5693	94	0.017
210	4120.9	4104.2	4105.1	2934	2920	2890	5773	5695	5580	5683	97	0.017
224	4121.5	4105.6	4104.9	2931	2923	2894	5763	5709	5595	5689	85	0.015
238	4122.3	4104.9	4104.8	2929	2917	2890	5756	5685	5580	5673	89	0.016
252	4121.8	4104.1	4104.6	2927	2914	2887	5747	5672	5568	5662	90	0.016
266	4122.4	4105.3	4105.2	2924	2915	2885	5736	5677	5561	5658	89	0.016
280	4122.9	4105.8	4105.7	2921	2911	2889	5725	5663	5577	5655	74	0.013
294	4123.1	4106.1	4105.9	2923	2912	2887	5733	5667	5570	5657	82	0.015
300	4123.4	4105.9	4105.4	2925	2910	2885	5742	5659	5561	5654	90	0.016

*i** means initial reading after 28 days of curing

Table A.25: Mass, frequency, and moduli of elasticity of 50% FA-0.38 specimens exposed to deionized water

	Mass of specimens (g)			**Frequency of specimens (Hz)**			**Moduli of elasticity of specimens (ksi)**					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4222.3	4163.5	4242.4	3020	2977	3021	6267	6005	6301	6191	162	0.026
14	4216.9	4157.7	4236.0	3033	2992	3031	6313	6058	6334	6235	154	0.025
28	4218.1	4158.4	4237.1	3043	3002	3044	6357	6099	6390	6282	159	0.025
43	4220.0	4159.8	4238.5	3055	3014	3054	6410	6150	6434	6331	157	0.025
56	4221.5	4161.2	4239.8	3064	3021	3062	6450	6181	6470	6367	161	0.025
70	4223.1	4163.4	4241.5	3075	3033	3074	6450	6181	6470	6367	161	0.025
85	4225.1	4165.8	4243.4	3086	3046	3085	6549	6290	6573	6471	157	0.024
99	4224.4	4165.0	4246.1	3092	3060	3096	6573	6347	6624	6515	147	0.023
112	4225.3	4165.4	4245.4	3100	3074	3107	6609	6406	6670	6562	138	0.021
127	4226.0	4166.2	4245.9	3102	3077	3111	6618	6420	6688	6575	139	0.021
141	4226.8	4166.8	4246.3	3105	3081	3114	6632	6437	6702	6590	137	0.021
155	4227.5	4167.3	4246.8	3103	3086	3119	6625	6459	6724	6603	134	0.020
168	4228.2	4168.2	4247.1	3104	3089	3122	6630	6473	6737	6614	133	0.020
183	4228.5	4168.7	4247.5	3105	3087	3124	6635	6465	6747	6616	142	0.021
196	4228.9	4169.3	4248.1	3108	3088	3126	6648	6471	6756	6625	144	0.022
210	4229.6	4169.9	4248.8	3105	3090	3123	6637	6480	6744	6620	133	0.020
224	4229.3	4170.5	4248.7	3110	3092	3129	6658	6489	6770	6639	141	0.021
238	4229.8	4170.7	4249.3	3114	3095	3132	6675	6502	6784	6654	142	0.021
252	4230.4	4170.2	4249.9	3119	3099	3130	6698	6518	6776	6664	132	0.020
266	4231.5	4171.4	4250.8	3125	3105	3134	6725	6545	6795	6689	129	0.019
280	4232.1	4172.0	4250.4	3128	3100	3139	6739	6525	6816	6694	151	0.023
294	4233.8	4172.9	4251.2	3123	3102	3133	6720	6535	6791	6682	132	0.020
300	4233.6	4173.4	4250.3	3126	3103	3136	6733	6540	6803	6692	136	0.020

*i** means initial reading after 28 days of curing

Table A.26: Mass, frequency, and moduli of elasticity of 50% FA-0.38 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4202.0	4201.5	4196.3	3000	2986	2998	6155	6097	6138	6130	30	0.005
14	4193.9	4194.8	4188.0	2992	2977	2991	6110	6051	6098	6086	32	0.005
28	4194.6	4196.2	4190.2	3000	2986	2999	6144	6089	6134	6122	29	0.005
43	4196.0	4198.1	4192.5	3008	2996	3008	6179	6133	6174	6162	25	0.004
56	4197.8	4199.5	4191.6	3015	3006	3017	6210	6176	6210	6199	20	0.003
70	4198.5	4201.8	4192.8	3023	3016	3026	6244	6220	6248	6238	15	0.002
85	4199.3	4200.2	4193.5	3031	3026	3034	6279	6259	6283	6274	12	0.002
99	4201.1	4202.5	4194.3	3037	3034	3045	6306	6296	6329	6311	17	0.003
112	4200.8	4203.4	4195.8	3043	3041	3050	6331	6326	6352	6337	14	0.002
127	4202.1	4204.6	4197.2	3045	3040	3051	6341	6324	6359	6341	17	0.003
141	4203.6	4206.0	4198.5	3044	3042	3049	6339	6335	6352	6342	9	0.001
155	4205.2	4207.5	4199.9	3045	3039	3050	6346	6324	6359	6343	17	0.003
168	4206.0	4208.8	4201.3	3047	3037	3048	6355	6318	6352	6342	21	0.003
183	4205.6	4208.9	4201.7	3048	3040	3053	6359	6331	6374	6354	22	0.003
196	4205.9	4209.4	4202.1	3050	3045	3051	6368	6352	6366	6362	9	0.001
210	4206.4	4209.7	4202.8	3049	3042	3056	6364	6340	6388	6364	24	0.004
224	4207.1	4210.5	4203.2	3052	3048	3060	6378	6366	6405	6383	20	0.003
238	4207.9	4211.2	4204.5	3055	3051	3066	6392	6380	6433	6401	28	0.004
252	4207.4	4211.9	4204.9	3058	3056	3069	6403	6402	6446	6417	25	0.004
266	4208.0	4212.4	4205.6	3062	3059	3075	6421	6415	6472	6436	31	0.005
280	4209.4	4213.2	4205.1	3065	3061	3071	6436	6425	6455	6438	15	0.002
294	4210.8	4214.2	4205.9	3064	3067	3075	6434	6452	6473	6453	19	0.003
300	4211.5	4214.5	4206.3	3066	3064	3073	6443	6439	6465	6449	14	0.002

*i** means initial reading after 28 days of curing

Table A.27: Mass, frequency, and moduli of elasticity of 50% FA-0.38 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4209.3	4215.5	4170.2	3015	3026	2998	6227	6282	6100	6203	93	0.015
14	4193.0	4199.4	4154.2	2980	2988	2963	6060	6102	5936	6033	86	0.014
28	4194.2	4200.6	4155.6	2984	2991	2968	6078	6116	5958	6051	83	0.014
43	4195.6	4202.8	4157.3	2988	2995	2973	6097	6136	5980	6071	81	0.013
56	4196.4	4204.1	4159.0	2993	2999	2978	6118	6154	6003	6092	79	0.013
70	4198.2	4206.8	4161.5	2996	3003	2983	6133	6174	6027	6111	76	0.012
85	4200.1	4207.4	4163.2	2999	3008	2988	6148	6196	6049	6131	75	0.012
99	4201.5	4209.8	4165.4	3002	3010	2990	6162	6208	6061	6144	75	0.012
112	4202.8	4211.6	4166.8	3005	3014	2993	6177	6227	6075	6159	77	0.013
127	4204.1	4213.0	4168.4	3003	3013	2990	6170	6225	6065	6153	81	0.013
141	4205.5	4214.5	4170.1	3000	3011	2986	6160	6219	6051	6143	85	0.014
155	4207.0	4215.7	4171.9	2996	3009	2983	6146	6212	6042	6133	86	0.014
168	4208.2	4217.0	4173.2	2998	3008	2981	6156	6210	6036	6134	89	0.015
183	4208.9	4216.8	4173.9	3000	3009	2983	6165	6214	6045	6141	87	0.014
196	4209.2	4217.6	4175.2	3001	3011	2984	6170	6223	6051	6148	88	0.014
210	4210.5	4218.3	4176.0	2999	3012	2986	6163	6228	6060	6151	85	0.014
224	4211.3	4219.6	4177.5	3002	3015	2988	6177	6243	6070	6163	87	0.014
238	4212.8	4220.5	4179.9	3004	3013	2985	6187	6236	6062	6162	90	0.015
252	4214.2	4222.0	4180.6	3003	3016	2989	6185	6250	6079	6171	87	0.014
266	4215.4	4223.4	4181.3	3007	3011	2992	6203	6232	6092	6176	74	0.012
280	4216.8	4225.3	4182.7	3005	3016	2991	6197	6255	6090	6181	84	0.014
294	4217.5	4226.4	4183.0	3004	3019	2993	6194	6269	6099	6187	86	0.014
300	4217.8	4226.8	4183.4	3006	3017	2991	6203	6262	6091	6185	87	0.014

*i** means initial reading after 28 days of curing

Table A.28: Mass, frequency, and moduli of elasticity of 50% FA-0.38 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4192.2	4211.8	4196.6	2990	3023	2993	6100	6264	6118	6161	90	0.015
14	4148.1	4168.1	4152.9	2931	2960	2933	5800	5944	5814	5853	79	0.014
28	4149.5	4169.2	4153.2	2935	2963	2936	5818	5957	5827	5867	78	0.013
43	4148.2	4169.4	4155.1	2940	2967	2940	5836	5974	5845	5885	77	0.013
56	4150.1	4170.5	4157.5	2943	2971	2944	5850	5991	5865	5902	78	0.013
70	4149.8	4171.0	4154.3	2948	2974	2947	5870	6004	5872	5915	77	0.013
85	4151.1	4172.3	4155.6	2952	2978	2949	5887	6022	5882	5930	79	0.013
99	4152.0	4172.8	4157.2	2955	2983	2952	5901	6043	5896	5947	84	0.014
112	4151.5	4171.7	4156.0	2956	2982	2955	5904	6037	5906	5949	76	0.013
127	4151.8	4172.1	4156.2	2957	2984	2957	5908	6046	5915	5956	78	0.013
141	4152.2	4173.1	4156.6	2959	2987	2960	5917	6060	5927	5968	80	0.013
155	4152.4	4172.9	4157.1	2961	2990	2962	5925	6072	5936	5978	82	0.014
168	4152.6	4172.8	4156.9	2960	2991	2961	5921	6076	5932	5976	86	0.014
183	4152.9	4172.3	4157.0	2958	2990	2960	5914	6071	5928	5971	87	0.015
196	4152.4	4173.1	4156.7	2956	2988	2962	5905	6064	5935	5968	84	0.014
210	4152.8	4173.6	4157.6	2955	2985	2959	5902	6052	5925	5960	81	0.014
224	4153.2	4173.9	4158.1	2953	2987	2957	5894	6061	5917	5958	90	0.015
238	4154.5	4174.3	4159.4	2952	2985	2955	5892	6053	5911	5952	88	0.015
252	4153.9	4174.0	4158.8	2955	2983	2953	5903	6045	5902	5950	82	0.014
266	4153.5	4174.9	4158.7	2956	2981	2955	5907	6038	5910	5952	75	0.013
280	4154.2	4175.0	4159.2	2954	2980	2951	5900	6034	5895	5943	79	0.013
294	4153.7	4174.9	4160.0	2952	2982	2954	5891	6042	5908	5947	83	0.014
300	4153.3	4174.8	4159.7	2950	2982	2953	5883	6042	5904	5943	87	0.015

*i** means initial reading after 28 days of curing

Table A.29: Mass, frequency, and moduli of elasticity of Control-0.44 specimens exposed to deionized water

	Mass of specimens (g)			**Frequency of specimens (Hz)**			**Moduli of elasticity of specimens (ksi)**					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4217.2	4122.6	4175.9	2970	2945	2987	6054	5819	6064	5979	139	0.023
14	4212.4	4118.8	4171.7	2980	2939	2980	6088	5790	6029	5969	158	0.026
28	4211.1	4116.8	4170.1	2991	2950	2995	6131	5831	6088	6017	162	0.027
42	4210.7	4115.9	4169.8	3003	2965	3014	6180	5889	6165	6078	164	0.027
56	4208.0	4113.4	4167.0	3006	2974	3017	6188	5921	6173	6094	150	0.025
71	4206.4	4111.0	4164.3	3005	2979	3015	6188	5921	6173	6094	150	0.025
87	4210.0	4115.4	4168.2	3018	2984	3026	6241	5964	6212	6139	152	0.025
99	4208.0	4113.7	4166.8	3035	2992	3031	6308	5994	6230	6177	164	0.027
114	4207.6	4113.6	4166.4	3030	3002	3048	6287	6034	6300	6207	150	0.024
126	4206.2	4112.5	4165.0	3036	3004	3048	6310	6040	6298	6216	152	0.025
140	4200.7	4114.5	4167.3	3036	3004	3048	6302	6043	6301	6215	149	0.024
155	4208.9	4114.6	4168.1	3042	3004	3047	6339	6043	6298	6227	160	0.026
168	4209.1	4115.3	4168.9	3043	3006	3050	6343	6052	6312	6236	160	0.026
182	4210.3	4116.5	4169.2	3046	3010	3051	6358	6070	6316	6248	156	0.025
197	4211.7	4118.0	4171.0	3049	3018	3057	6372	6105	6344	6274	147	0.023
211	4212.1	4118.5	4171.9	3052	3019	3058	6385	6109	6349	6281	150	0.024
224	4212.9	4118.9	4172.1	3055	3020	3063	6399	6114	6371	6295	157	0.025
238	4213.1	4119.2	4172.4	3057	3022	3066	6408	6122	6383	6305	158	0.025
253	4213.6	4119.5	4172.9	3059	3021	3068	6417	6119	6393	6310	166	0.026
266	4214.5	4119.9	4173.8	3063	3022	3070	6435	6124	6402	6320	171	0.027
280	4212.7	4118.8	4172.9	3068	3030	3066	6454	6154	6384	6331	157	0.025
294	4212.5	4118.6	4172.1	3065	3028	3069	6441	6146	6396	6327	159	0.025
300	4212.9	4118.3	4172.3	3062	3030	3073	6429	6154	6412	6332	154	0.024

*i** means initial reading after 28 days of curing

Table A.30: Mass, frequency, and moduli of elasticity of Control-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4079.5	4111.4	4153.5	2960	2970	2965	5817	5902	5943	5887	64	0.011
14	4077.5	4109.6	4151.3	2941	2947	2947	5740	5809	5868	5806	64	0.011
28	4078.4	4110.0	4152.0	2960	2965	2963	5816	5881	5933	5876	59	0.010
42	4077.9	4109.4	4151.5	2972	2968	2975	5862	5892	5980	5911	61	0.010
56	4077.1	4108.9	4150.9	2976	2978	2980	5877	5931	5999	5936	61	0.010
71	4077.3	4108.8	4151.0	2983	2977	2979	5905	5927	5995	5942	47	0.008
87	4080.5	4112.2	4154.6	2992	2991	2991	5945	5987	6049	5994	52	0.009
99	4078.8	4111.1	4152.6	2987	2992	2993	5923	5990	6054	5989	66	0.011
114	4079.3	4111.0	4153.2	2992	2994	3001	5943	5998	6088	6010	73	0.012
126	4079.5	4111.0	4153.3	2994	2996	3000	5952	6006	6084	6014	66	0.011
140	4081.3	4111.9	4153.5	2999	2999	3004	5974	6019	6100	6031	64	0.011
155	4081.8	4112.3	4155.0	3000	3005	3019	5979	6044	6163	6062	94	0.015
168	4082.3	4113.1	4155.9	3001	3009	3018	5984	6061	6161	6068	89	0.015
182	4083.0	4114.6	4156.4	3005	3012	3019	6001	6075	6166	6080	83	0.014
197	4083.8	4115.9	4157.8	3011	3018	3019	6026	6101	6168	6098	71	0.012
211	4082.9	4114.6	4156.3	3012	3018	3020	6028	6099	6169	6099	71	0.012
224	4082.4	4114.0	4156.0	3014	3019	3023	6036	6103	6181	6107	73	0.012
238	4082.3	4113.8	4155.8	3016	3020	3026	6044	6106	6193	6114	75	0.012
253	4083.5	4115.2	4157.6	3017	3020	3027	6049	6108	6200	6119	76	0.012
266	4085.9	4117.7	4160.0	3019	3021	3030	6061	6116	6216	6131	79	0.013
280	4086.9	4117.7	4160.5	3013	3015	3020	6038	6092	6176	6102	69	0.011
294	4086.3	4117.5	4160.7	3014	3013	3017	6041	6084	6164	6096	62	0.010
300	4086.1	4117.4	4160.2	3011	3012	3014	6029	6079	6151	6086	61	0.010

*i** means initial reading after 28 days of curing

Table A.31: Mass, frequency, and moduli of elasticity of Control-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3		1	2	3	Average	Std Dev	COV
*i**	4147.5	4147.5	4157.3	2990	2980	2999		6035	5994	6085	6038	46	0.008
14	4138.3	4141.0	4150.8	2927	2920	2929		5770	5746	5796	5771	25	0.004
28	4144.4	4147.2	4154.9	2890	2875	2882		5634	5579	5617	5610	28	0.005
42	4141.0	4137.4	4148.6	2847	2830	2841		5463	5393	5450	5435	37	0.007
56	4130.0	4127.1	4140.3	2830	2814	2814		5383	5319	5336	5346	33	0.006
71	4119.8	4121.2	4139.3	2784	2755	2756		5197	5091	5117	5135	55	0.011
87	4115.4	4121.8	4138.3	2754	2710	2717		5080	4927	4972	4993	79	0.016
99	4106.7	4117.8	4116.5	2705	2670	2697		4891	4778	4873	4847	61	0.013
114	4075.7	4097.2	4077.0	2662	2622	2658		4701	4584	4688	4658	64	0.014
126	3999.0	4038.4	3986.5	2670	2618	2668		4640	4505	4618	4588	73	0.016
140	3937.2	3984.8	3933.7	2619	2571	2640		4395	4287	4462	4381	88	0.020
155	3895.0	3906.7	3882.7	2570	2550	2593		4187	4134	4249	4190	57	0.014
168	3881.0	3895.2	3859.1	2520	2501	2542		4011	3965	4058	4012	47	0.012
182	3862.0	3880.1	3843.3	2480	2472	2523		3866	3859	3982	3902	69	0.018
197	3853.1	3874.9	3832.1	2448	2451	2500		3758	3789	3898	3815	74	0.019
211	3810.8	3845.0	3801.0	2426	2433	2482		3650	3704	3811	3722	82	0.022
224	3775.0	3839.0	3785.0	2413	2400	2455		3577	3599	3713	3630	73	0.020
238	3744.3	3830.0	3765.6	2400	2380	2434		3510	3531	3631	3557	65	0.018
253	3703.1	3802.6	3743.2	2395	2370	2422		3457	3476	3574	3502	63	0.018
266	3641.0	3776.6	3718.4	2391	2356	2394		3388	3412	3468	3423	41	0.012
280	3561.5	3708.5	3658.2	2397	2349	2387		3330	3330	3392	3351	36	0.011
294	3478.5	3640.5	3579.2	2381	2314	2376		3210	3173	3289	3224	59	0.018
300	3449.1	3626.0	3555.7	2375	2303	2369		3166	3130	3248	3181	60	0.019

*i** means initial reading after 28 days of curing

Table A.32: Mass, frequency, and moduli of elasticity of Control-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4117.9	4148.1	4147.6	2970	2979	2984		5912	5991	6011	5971	52	0.009
14	4084.5	4115.8	4115.9	2942	2944	2954		5754	5806	5845	5802	46	0.008
28	4084.0	4115.4	4116.1	2937	2942	2951		5734	5797	5834	5788	51	0.009
42	4084.8	4115.9	4117.2	2942	2950	2957		5754	5830	5859	5814	54	0.009
56	4085.3	4116.6	4116.8	2932	2936	2947		5716	5775	5819	5770	52	0.009
71	4085.1	4116.9	4117.6	2913	2914	2921		5642	5690	5718	5683	38	0.007
87	4090.3	4124.0	4123.9	2909	2915	2920		5633	5703	5723	5686	47	0.008
99	4086.7	4122.6	4121.0	2913	2914	2924		5644	5697	5734	5692	45	0.008
114	4087.3	4124.6	4122.8	2904	2900	2913		5610	5646	5694	5650	42	0.007
126	4087.6	4126.3	4123.5	2898	2891	2905		5587	5613	5664	5621	39	0.007
140	4090.2	4128.0	4126.2	2896	2888	2904		5583	5604	5663	5617	42	0.007
155	4099.0	4137.6	4134.3	2870	2866	2872		5495	5531	5550	5525	28	0.005
168	4108.3	4143.4	4143.1	2865	2860	2866		5488	5516	5539	5514	25	0.005
182	4111.5	4153.6	4150.2	2859	2851	2863		5470	5495	5537	5500	34	0.006
197	4118.8	4160.5	4155.5	2855	2839	2860		5464	5458	5532	5485	41	0.008
211	4120.2	4165.6	4159.2	2845	2829	2851		5428	5426	5502	5452	44	0.008
224	4128.9	4170.3	4163.1	2828	2808	2843		5374	5352	5476	5401	66	0.012
238	4139.3	4178.3	4166.2	2819	2795	2832		5354	5312	5438	5368	64	0.012
253	4143.5	4183.6	4169.8	2808	2787	2821		5317	5289	5401	5336	58	0.011
266	4151.8	4187.8	4175.5	2800	2781	2816		5298	5271	5389	5319	62	0.012
280	4159.2	4193.9	4177.5	2760	2740	2788		5156	5124	5285	5189	85	0.016
294	4164.7	4198.2	4182.2	2736	2712	2763		5074	5025	5196	5099	88	0.017
300	4166.7	4199.7	4184.5	2727	2702	2755		5043	4990	5169	5067	92	0.018

*i** means initial reading after 28 days of curing

Table A.33: Mass, frequency, and moduli of elasticity of 20% SL-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4135.4	4177.6	4135.9	3001	2992	2987	6061	6087	6006	6051	41	0.007
14	4133.6	4174.3	4134.1	2981	2965	2968	5978	5973	5927	5959	28	0.005
28	4132.5	4173.4	4132.2	3002	2985	2982	6061	6052	5980	6031	44	0.007
42	4130.0	4171.5	4130.6	3013	3000	2999	6102	6110	6046	6086	35	0.006
56	4127.1	4167.7	4127.6	3020	2995	2996	6126	6084	6030	6080	48	0.008
72	4131.1	4171.8	4132.3	3020	3000	3010	6126	6084	6030	6080	48	0.008
89	4129.7	4170.4	4130.7	3036	3020	3020	6195	6190	6131	6172	35	0.006
104	4129.4	4171.3	4130.4	3042	3030	3031	6219	6233	6176	6209	30	0.005
114	4130.5	4170.8	4130.7	3046	3031	3033	6237	6236	6184	6219	30	0.005
126	4129.8	4170.6	4129.8	3050	3033	3037	6253	6244	6199	6232	29	0.005
140	4130.1	4171.0	4131.2	3051	3035	3038	6257	6253	6206	6239	29	0.005
155	4131.2	4171.8	4132.4	3052	3039	3040	6263	6271	6216	6250	30	0.005
168	4133.3	4173.8	4134.3	3053	3042	3045	6270	6286	6239	6265	24	0.004
182	4133.8	4174.1	4134.8	3055	3044	3048	6279	6295	6252	6275	22	0.003
197	4134.1	4174.8	4135.1	3058	3047	3050	6292	6308	6261	6287	24	0.004
210	4134.1	4175.5	4135.7	3063	3050	3054	6313	6322	6278	6304	23	0.004
224	4133.8	4175.2	4135.1	3065	3056	3059	6320	6346	6298	6321	24	0.004
238	4133.3	4175.0	4135.6	3070	3063	3062	6340	6375	6311	6342	32	0.005
254	4133.6	4174.4	4134.5	3065	3057	3058	6320	6349	6293	6321	28	0.004
267	4134.6	4175.5	4136.3	3070	3055	3050	6342	6342	6262	6316	46	0.007
280	4134.8	4175.9	4136.5	3072	3054	3051	6351	6339	6267	6319	45	0.007
294	4135.6	4176.2	4136.0	3071	3052	3052	6348	6331	6270	6316	41	0.006
300	4136.0	4176.4	4136.1	3071	3053	3053	6348	6336	6274	6319	40	0.006

*i** means initial reading after 28 days of curing

Table A.34: Mass, frequency, and moduli of elasticity of 20% SL-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4128.4	4131.8	4172.4	2981	2997	3026	5971	6040	6218	6076	128	0.021
14	4131.6	4134.9	4174.8	2951	2975	3003	5856	5956	6127	5980	137	0.023
28	4131.3	4134.7	4176.0	2965	2990	3015	5911	6016	6178	6035	135	0.022
42	4129.9	4134.0	4174.7	2990	2997	3027	6009	6043	6226	6093	116	0.019
56	4130.7	4134.9	4175.4	2980	2993	3025	5970	6028	6218	6072	130	0.021
72	4133.2	4137.7	4176.9	2986	3000	3029	5998	6061	6237	6099	124	0.020
89	4132.6	4136.1	4176.6	2994	3009	3037	6029	6095	6270	6131	124	0.020
104	4132.8	4137.2	4177.1	3006	3020	3048	6078	6141	6316	6178	123	0.020
114	4132.5	4136.5	4176.6	3010	3019	3048	6094	6136	6315	6182	118	0.019
126	4132.2	4136.2	4176.6	3006	3021	3051	6077	6144	6328	6183	130	0.021
140	4132.8	4136.8	4177.3	3008	3025	3055	6086	6161	6345	6197	133	0.022
155	4133.1	4137.2	4179.3	3010	3028	3058	6094	6174	6361	6210	137	0.022
168	4134.4	4138.7	4180.7	3014	3031	3062	6113	6188	6379	6227	138	0.022
182	4134.9	4139.2	4180.9	3019	3036	3063	6134	6209	6384	6242	128	0.021
197	4135.1	4139.8	4181.0	3025	3039	3064	6158	6223	6388	6256	119	0.019
210	4135.6	4140.5	4181.1	3030	3042	3065	6179	6236	6393	6269	110	0.018
224	4135.3	4140.2	4180.6	3031	3043	3069	6183	6240	6409	6277	117	0.019
238	4135.1	4139.3	4179.3	3030	3044	3075	6179	6242	6432	6284	132	0.021
254	4136.0	4140.7	4180.8	3022	3041	3065	6147	6232	6392	6257	124	0.020
267	4137.6	4141.2	4181.3	3030	3038	3068	6182	6221	6405	6269	119	0.019
280	4137.2	4140.8	4181.8	3027	3038	3069	6170	6220	6410	6267	127	0.020
294	4136.8	4141.1	4180.2	3025	3039	3067	6161	6224	6400	6262	124	0.020
300	4136.3	4140.5	4180.7	3025	3037	3066	6160	6215	6396	6257	123	0.020

*i** means initial reading after 28 days of curing

Table A.35: Mass, frequency, and moduli of elasticity of 20% SL-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4123.6	4155.3	4132.0	2978	2992	2984	5952	6054	5988	5998	52	0.009
14	4118.2	4151.1	4126.9	2942	2952	2955	5801	5887	5865	5851	45	0.008
28	4121.9	4154.5	4130.2	2938	2948	2946	5791	5876	5834	5834	43	0.007
42	4125.2	4158.2	4133.6	2936	2949	2949	5787	5885	5851	5841	50	0.009
56	4129.9	4163.8	4138.9	2896	2909	2909	5637	5735	5700	5691	49	0.009
72	4137.1	4170.8	4144.7	2880	2892	2892	5585	5677	5642	5635	47	0.008
89	4145.5	4179.0	4153.2	2876	2885	2886	5581	5661	5630	5624	41	0.007
104	4153.5	4186.2	4160.5	2870	2880	2878	5568	5651	5609	5609	42	0.007
114	4155.8	4187.8	4163.2	2864	2875	2875	5548	5634	5601	5594	43	0.008
126	4157.8	4189.8	4166.4	2858	2870	2872	5527	5617	5593	5579	46	0.008
140	4159.6	4193.5	4170.2	2853	2864	2864	5510	5598	5567	5559	45	0.008
155	4162.8	4196.7	4173.5	2849	2858	2859	5499	5579	5552	5543	41	0.007
168	4167.7	4200.2	4178.4	2846	2853	2854	5494	5564	5539	5532	36	0.006
182	4169.8	4203.5	4179.5	2835	2845	2844	5454	5537	5502	5498	42	0.008
197	4173.8	4205.2	4180.2	2826	2839	2838	5425	5516	5480	5474	46	0.008
210	4177.6	4207.8	4182.9	2817	2833	2832	5395	5496	5460	5451	51	0.009
224	4179.8	4210.7	4184.2	2809	2822	2825	5368	5458	5435	5420	47	0.009
238	4182.8	4214.1	4188.4	2798	2806	2816	5330	5400	5406	5378	42	0.008
254	4184.5	4215.7	4191.0	2773	2783	2788	5237	5314	5302	5284	41	0.008
267	4187.0	4217.6	4192.8	2768	2771	2780	5221	5271	5274	5255	30	0.006
280	4187.8	4219.2	4194.1	2761	2768	2775	5196	5261	5256	5238	37	0.007
294	4188.7	4220.5	4196.5	2752	2763	2773	5163	5244	5252	5220	49	0.009
300	4189.6	4221.2	4197.0	2745	2761	2771	5138	5237	5245	5207	60	0.011

*i** means initial reading after 28 days of curing

Table A.36: Mass, frequency, and moduli of elasticity of 20% SL-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4157.3	4136.9	4169.4	3013	2998	3021	6142	6052	6193	6129	72	0.012
14	4132.9	4112.0	4144.1	2955	2931	2958	5873	5749	5901	5841	81	0.014
28	4132.7	4111.6	4143.8	2953	2941	2954	5865	5788	5885	5846	51	0.009
42	4132.3	4111.0	4142.9	2962	2946	2956	5900	5807	5892	5866	52	0.009
56	4133.1	4112.0	4143.7	2933	2911	2930	5787	5671	5790	5749	68	0.012
72	4134.6	4113.6	4145.4	2932	2906	2925	5785	5654	5772	5737	72	0.013
89	4134.7	4113.6	4145.7	2935	2914	2929	5797	5685	5788	5757	62	0.011
104	4134.0	4113.1	4144.1	2926	2905	2916	5760	5649	5735	5715	58	0.010
114	4132.5	4111.8	4143.4	2931	2910	2920	5778	5667	5750	5732	58	0.010
126	4132.1	4110.8	4142.9	2914	2894	2909	5711	5603	5706	5673	61	0.011
140	4133.1	4112.2	4143.8	2920	2899	2912	5735	5625	5719	5693	60	0.010
155	4135.6	4113.5	4145.6	2929	2902	2918	5774	5638	5745	5719	72	0.013
168	4137.2	4116.2	4148.4	2936	2909	2924	5804	5669	5772	5749	71	0.012
182	4137.3	4116.8	4148.5	2935	2910	2926	5800	5674	5781	5752	68	0.012
197	4137.5	4117.2	4148.3	2937	2911	2927	5809	5678	5784	5757	69	0.012
210	4137.7	4117.1	4148.4	2936	2915	2930	5805	5694	5796	5765	62	0.011
224	4138.2	4117.8	4149.1	2937	2917	2931	5810	5702	5801	5771	60	0.010
238	4139.4	4118.6	4150.9	2939	2920	2931	5819	5715	5804	5779	56	0.010
254	4139.6	4118.0	4150.4	2936	2917	2938	5808	5703	5831	5780	68	0.012
267	4141.4	4120.8	4152.8	2926	2910	2928	5771	5679	5794	5748	61	0.011
280	4133.1	4149.9	4156.6	2919	2918	2928	5732	5751	5800	5761	35	0.006
294	4146.5	4150.9	4161.1	2925	2909	2927	5774	5717	5802	5764	43	0.008
300	4152.6	4165.4	4163.2	2931	2906	2927	5806	5725	5805	5779	46	0.008

*i** means initial reading after 28 days of curing

Table A.37: Mass, frequency, and moduli of elasticity of 35% SL-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4131.8	4154.9	4096.1	3018	3009	3000	6125	6123	6000	6082	72	0.012
14	4130.5	4152.2	4093.9	2996	2984	2981	6034	6017	5921	5991	61	0.010
29	4133.0	4156.4	4097.0	3014	2999	2994	6111	6084	5977	6057	71	0.012
45	4136.6	4160.0	4101.4	3038	3024	3014	6214	6191	6064	6156	81	0.013
57	4134.9	4158.1	4099.5	3037	3024	3021	6207	6188	6089	6162	63	0.010
72	4134.8	4158.4	4099.3	3052	3038	3035	6207	6188	6089	6162	63	0.010
84	4133.7	4156.7	4098.8	3053	3040	3038	6271	6252	6157	6227	61	0.010
98	4136.0	4159.2	4100.6	3054	3050	3040	6278	6297	6168	6248	70	0.011
112	4136.8	4160.3	4101.8	3061	3055	3048	6308	6319	6202	6277	65	0.010
126	4137.3	4161.1	4103.2	3068	3058	3054	6338	6333	6229	6300	62	0.010
140	4137.7	4161.8	4103.8	3073	3061	3056	6359	6347	6238	6314	67	0.011
155	4138.4	4162.7	4104.1	3078	3063	3059	6381	6356	6250	6329	69	0.011
168	4139.0	4163.1	4104.6	3080	3064	3060	6390	6361	6255	6335	71	0.011
182	4137.5	4162.8	4104.2	3083	3065	3062	6400	6365	6263	6343	71	0.011
197	4138.2	4161.9	4103.5	3085	3067	3063	6410	6372	6266	6349	75	0.012
212	4136.5	4160.7	4102.0	3086	3067	3063	6411	6370	6263	6348	76	0.012
224	4137.1	4161.3	4102.8	3086	3068	3066	6412	6375	6277	6355	70	0.011
238	4138.3	4161.6	4104.4	3084	3071	3068	6406	6388	6288	6360	64	0.010
252	4138.0	4161.9	4104.2	3086	3074	3070	6414	6401	6296	6370	65	0.010
266	4137.6	4162.5	4104.5	3090	3076	3072	6430	6410	6304	6381	67	0.011
280	4137.8	4163.1	4104.4	3091	3077	3071	6434	6415	6300	6383	73	0.011
294	4140.2	4165.7	4105.8	3090	3079	3073	6434	6427	6310	6390	70	0.011
300	4142.4	4166.5	4107.5	3091	3080	3076	6441	6433	6325	6400	65	0.010

*i** means initial reading after 28 days of curing

Table A.38: Mass, frequency, and moduli of elasticity of 35% SL-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4119.4	4135.5	4155.3	3000	3003	3036	6034	6070	6234	6112	106	0.017
14	4122.6	4138.4	4158.7	2975	2980	3015	5938	5981	6153	6024	113	0.019
29	4125.5	4140.7	4161.1	2982	2987	3017	5971	6013	6164	6049	102	0.017
45	4129.4	4145.1	4165.9	2997	3007	3030	6037	6100	6225	6120	96	0.016
57	4129.3	4144.7	4164.7	2998	3005	3036	6040	6091	6248	6126	108	0.018
72	4130.7	4145.5	4166.3	3010	3018	3044	6091	6145	6283	6173	99	0.016
84	4130.7	4145.5	4165.6	3010	3015	3044	6091	6133	6282	6169	100	0.016
98	4131.2	4144.3	4165.8	3010	3020	3047	6092	6152	6295	6179	104	0.017
112	4131.4	4144.8	4166.1	3018	3023	3051	6124	6165	6312	6200	99	0.016
126	4134.1	4145.2	4167.4	3027	3026	3057	6165	6177	6338	6227	97	0.016
140	4132.1	4145.6	4167.5	3026	3031	3058	6158	6198	6343	6233	97	0.016
155	4133.2	4145.9	4167.6	3027	3037	3060	6164	6224	6351	6246	96	0.015
168	4134.8	4146.8	4167.6	3027	3040	3060	6166	6237	6351	6251	93	0.015
182	4134.2	4146.9	4168.1	3028	3036	3061	6169	6221	6356	6249	97	0.015
197	4135.1	4147.5	4169.5	3027	3032	3063	6166	6205	6367	6246	106	0.017
212	4134.9	4147.1	4169.2	3027	3033	3064	6166	6209	6370	6248	108	0.017
224	4134.2	4147.4	4168.8	3027	3036	3065	6165	6222	6374	6254	108	0.017
238	4135.0	4147.5	4169.0	3026	3036	3064	6162	6222	6370	6251	107	0.017
252	4135.5	4147.6	4169.5	3027	3038	3066	6167	6230	6379	6259	109	0.017
266	4135.9	4147.3	4168.9	3029	3040	3069	6176	6238	6391	6268	111	0.018
280	4135.6	4147.0	4169.2	3030	3041	3071	6179	6242	6399	6273	113	0.018
294	4140.8	4151.6	4172.1	3033	3041	3068	6199	6248	6391	6280	100	0.016
300	4141.5	4153.0	4175.9	3032	3040	3064	6196	6246	6380	6274	95	0.015

*i** means initial reading after 28 days of curing

Table A.39: Mass, frequency, and moduli of elasticity of 35% SL-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4165.6	4139.0	4136.9	3031	3006	2971	6228	6087	5943	6086	143	0.023
14	4160.3	4135.1	4133.3	2987	2964	2936	6041	5912	5799	5917	121	0.020
29	4166.1	4141.1	4138.7	2976	2953	2925	6005	5877	5763	5882	121	0.021
45	4177.0	4149.9	4148.0	2987	2963	2936	6065	5930	5819	5938	123	0.021
57	4177.6	4151.9	4149.8	2966	2961	2933	5981	5924	5810	5905	87	0.015
72	4180.5	4154.6	4152.6	2983	2959	2932	6054	5920	5810	5928	122	0.021
84	4181.8	4156.6	4154.5	2983	2960	2933	6056	5927	5817	5933	120	0.020
98	4184.9	4158.9	4156.9	2982	2955	2931	6057	5910	5812	5926	123	0.021
112	4186.8	4160.6	4158.8	2976	2950	2926	6035	5893	5795	5908	121	0.020
126	4190.5	4164.8	4162.5	2972	2946	2922	6024	5883	5784	5897	121	0.020
140	4192.1	4166.7	4164.3	2969	2945	2920	6014	5882	5779	5891	118	0.020
155	4194.5	4167.9	4165.4	2967	2944	2918	6010	5879	5772	5887	119	0.020
168	4195.3	4169.9	4168.3	2966	2942	2917	6007	5874	5772	5884	117	0.020
182	4197.5	4171.6	4170.5	2959	2935	2911	5981	5849	5752	5861	115	0.020
197	4200.1	4174.4	4173.0	2952	2929	2902	5957	5829	5720	5835	119	0.020
212	4202.6	4176.9	4174.5	2947	2920	2894	5940	5796	5690	5809	126	0.022
224	4202.9	4177.3	4175.1	2945	2917	2891	5933	5785	5679	5799	127	0.022
238	4203.7	4178.0	4176.0	2941	2910	2890	5918	5758	5677	5784	123	0.021
252	4204.5	4179.6	4177.9	2937	2908	2889	5903	5752	5675	5777	116	0.020
266	4206.8	4180.4	4178.5	2933	2905	2887	5890	5742	5668	5767	113	0.020
280	4207.3	4181.3	4179.9	2931	2903	2891	5882	5735	5686	5768	102	0.018
294	4211.4	4186.5	4184.9	2924	2890	2875	5860	5691	5630	5727	119	0.021
300	4215.8	4188.1	4186.4	2921	2886	2871	5854	5677	5616	5716	124	0.022

*i** means initial reading after 28 days of curing

Table A.40: Mass, frequency, and moduli of elasticity of 35% SL-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			**Frequency of specimens (Hz)**			**Moduli of elasticity of specimens (ksi)**					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4154.2	4115.5	4112.2	3021	3008	2975	6170	6060	5923	6051	124	0.020
14	4134.7	4097.0	4093.5	2960	2953	2923	5896	5815	5692	5801	103	0.018
29	4134.5	4095.9	4092.8	2944	2938	2906	5832	5754	5625	5737	104	0.018
45	4137.2	4098.1	4095.5	2956	2946	2913	5884	5789	5656	5776	114	0.020
57	4134.9	4095.9	4093.0	2950	2946	2913	5856	5786	5653	5765	103	0.018
72	4134.2	4096.6	4093.0	2944	2941	2908	5832	5767	5633	5744	101	0.018
84	4133.9	4095.2	4092.5	2936	2935	2899	5800	5741	5598	5713	104	0.018
98	4134.6	4095.4	4092.5	2940	2939	2903	5816	5757	5613	5729	105	0.018
112	4137.4	4098.1	4094.6	2940	2938	2903	5820	5757	5616	5731	105	0.018
126	4139.5	4100.8	4097.7	2939	2937	2904	5819	5757	5624	5734	100	0.017
140	4139.8	4100.7	4097.9	2943	2939	2906	5836	5765	5632	5744	103	0.018
155	4140.1	4100.6	4098.2	2946	2940	2910	5848	5769	5648	5755	101	0.017
168	4140.2	4100.7	4098.3	2950	2942	2911	5864	5777	5652	5764	106	0.018
182	4139.5	4101.5	4098.1	2949	2940	2910	5859	5770	5648	5759	106	0.018
197	4140.3	4101.0	4097.5	2945	2938	2908	5844	5761	5639	5748	103	0.018
212	4139.7	4101.3	4097.9	2942	2938	2906	5832	5762	5632	5742	101	0.018
224	4140.3	4102.1	4098.6	2944	2938	2904	5840	5763	5625	5743	109	0.019
238	4142.1	4102.6	4099.8	2944	2936	2899	5843	5756	5608	5735	119	0.021
252	4142.6	4102.3	4100.2	2942	2939	2895	5836	5767	5593	5732	125	0.022
266	4142.3	4102.8	4099.9	2940	2937	2900	5827	5760	5612	5733	110	0.019
280	4142.5	4102.4	4099.7	2941	2940	2903	5831	5771	5623	5742	107	0.019
294	4143.5	4106.8	4102.4	2938	2934	2904	5821	5754	5631	5735	97	0.017
300	4144.1	4107.2	4103.3	2937	2935	2902	5818	5758	5624	5733	99	0.017

*i** means initial reading after 28 days of curing

Table A.41: Mass, frequency, and moduli of elasticity of 50% SL-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4124.9	4133.2	4124.6	3010	3000	3007		6082	6054	6070	6069	14	0.002
14	4124.7	4132.2	4123.0	2985	2974	2982		5981	5948	5967	5966	17	0.003
31	4125.9	4134.2	4124.4	2996	2986	2993		6027	5999	6013	6013	14	0.002
44	4131.6	4139.7	4129.3	3013	3002	3003		6104	6072	6061	6079	23	0.004
59	4130.7	4137.8	4128.1	3030	3016	3022		6172	6126	6136	6145	24	0.004
74	4129.9	4137.3	4128.0	3031	3025	3032		6172	6126	6136	6145	24	0.004
84	4130.2	4137.8	4127.5	3035	3032	3033		6192	6191	6180	6187	7	0.001
98	4132.0	4140.1	4129.5	3040	3035	3033		6215	6207	6183	6201	17	0.003
112	4132.4	4140.2	4129.7	3045	3037	3035		6236	6215	6191	6214	22	0.004
126	4132.9	4140.5	4130.1	3049	3039	3039		6253	6224	6208	6228	23	0.004
140	4133.5	4140.9	4131.7	3052	3040	3042		6266	6228	6223	6239	24	0.004
155	4134.2	4141.5	4131.7	3055	3043	3046		6280	6241	6239	6253	23	0.004
168	4134.9	4142.0	4131.9	3057	3048	3049		6289	6263	6252	6268	19	0.003
183	4135.4	4142.3	4131.9	3060	3054	3053		6302	6288	6268	6286	17	0.003
197	4135.0	4141.5	4131.1	3064	3057	3054		6318	6299	6271	6296	24	0.004
213	4134.2	4140.8	4129.0	3069	3059	3055		6337	6306	6272	6305	33	0.005
225	4133.3	4139.5	4129.1	3071	3060	3055		6344	6308	6272	6308	36	0.006
238	4134.1	4140.5	4131.0	3070	3058	3068		6341	6302	6328	6324	20	0.003
252	4134.5	4141.2	4130.9	3073	3060	3069		6354	6311	6332	6333	22	0.003
266	4134.3	4140.9	4131.2	3072	3063	3068		6350	6323	6329	6334	14	0.002
280	4134.0	4141.0	4130.6	3073	3065	3068		6354	6331	6328	6338	14	0.002
294	4135.8	4142.6	4132.5	3073	3063	3064		6356	6325	6314	6332	22	0.003
300	4136.5	4143.5	4133.4	3071	3059	3056		6349	6310	6283	6314	33	0.005

*i** means initial reading after 28 days of curing

Table A.42: Mass, frequency, and moduli of elasticity of 50% SL-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3		1	2	3	Average	Std Dev	COV
*i**	4119.4	4172.1	4100.9	3020	3036	2985		6115	6259	5947	6107	156	0.026
14	4120.4	4174.5	4101.9	2990	3010	2960		5995	6156	5849	6000	153	0.026
31	4124.1	4177.0	4104.9	2997	3015	2969		6029	6180	5889	6033	145	0.024
44	4127.5	4180.9	4108.3	2998	3020	2968		6038	6206	5890	6045	158	0.026
59	4126.1	4179.3	4107.6	3020	3030	2979		6125	6245	5933	6101	157	0.026
74	4128.0	4180.4	4108.9	3020	3041	2986		6127	6292	5963	6127	165	0.027
84	4128.6	4180.4	4109.7	3025	3048	2991		6149	6321	5984	6151	169	0.027
98	4130.1	4181.4	4111.3	3025	3044	2990		6151	6306	5982	6146	162	0.026
112	4130.7	4182.3	4112.0	3028	3048	2995		6164	6324	6003	6164	160	0.026
126	4131.2	4183.0	4112.7	3032	3051	2998		6181	6337	6016	6178	161	0.026
140	4131.6	4184.4	4113.2	3036	3053	3004		6198	6348	6041	6196	153	0.025
155	4132.5	4184.0	4113.6	3039	3055	3008		6212	6355	6058	6208	149	0.024
168	4133.2	4184.2	4114.0	3041	3057	3011		6221	6364	6070	6218	147	0.024
183	4133.6	4183.9	4114.1	3042	3060	3015		6225	6376	6087	6229	145	0.023
197	4134.2	4185.2	4115.2	3044	3062	3013		6235	6386	6080	6234	153	0.025
213	4135.8	4186.2	4116.8	3045	3065	3010		6241	6400	6070	6237	165	0.026
225	4135.4	4186.4	4116.3	3033	3065	3008		6191	6401	6062	6218	171	0.028
238	4134.9	4185.7	4115.3	3040	3069	3013		6219	6416	6080	6239	169	0.027
252	4135.5	4185.4	4115.2	3041	3070	3010		6224	6420	6068	6237	176	0.028
266	4135.8	4186.1	4115.8	3042	3066	3016		6229	6404	6093	6242	156	0.025
280	4135.1	4185.9	4115.4	3044	3065	3014		6236	6400	6085	6240	158	0.025
294	4137.6	4188.9	4118.8	3041	3060	3011		6227	6384	6077	6229	153	0.025
300	4139.9	4190.7	4120.7	3040	3056	3010		6227	6370	6076	6224	147	0.024

*i** means initial reading after 28 days of curing

Table A.43: Mass, frequency, and moduli of elasticity of 50% SL-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4137.6	4100.6	4156.9	3024	2991	3020	6158	5970	6170	6100	112	0.018
14	4136.5	4099.0	4156.7	2989	2963	2988	6015	5857	6040	5971	99	0.017
31	4143.0	4105.7	4163.1	2976	2952	2977	5972	5823	6005	5933	97	0.016
44	4148.4	4111.1	4169.1	2977	2952	2976	5984	5831	6009	5941	97	0.016
59	4151.2	4114.4	4173.1	2982	2955	2989	6008	5847	6068	5974	114	0.019
74	4154.0	4117.1	4174.4	2980	2954	2980	6004	5847	6033	5961	100	0.017
84	4154.0	4117.5	4175.1	2982	2963	2982	6012	5883	6042	5979	84	0.014
98	4155.8	4119.9	4175.8	2991	2970	2994	6051	5915	6092	6019	93	0.015
112	4156.5	4120.5	4176.3	2991	2970	2992	6052	5915	6085	6017	90	0.015
126	4157.2	4121.3	4177.1	2990	2970	2989	6049	5917	6074	6013	84	0.014
140	4158.0	4122.1	4177.5	2990	2970	2986	6050	5918	6062	6010	80	0.013
155	4158.2	4122.5	4178.1	2986	2968	2986	6034	5910	6063	6002	81	0.014
168	4158.6	4122.8	4178.8	2981	2967	2987	6014	5907	6068	5996	82	0.014
183	4158.5	4123.0	4178.9	2979	2965	2987	6006	5899	6068	5991	86	0.014
197	4159.2	4125.2	4179.4	2972	2959	2981	5979	5878	6045	5967	84	0.014
213	4160.2	4126.8	4181.6	2965	2953	2974	5952	5857	6019	5943	82	0.014
225	4160.9	4126.0	4182.3	2960	2948	2968	5933	5836	5996	5922	81	0.014
238	4160.7	4126.6	4182.0	2975	2954	2980	5993	5861	6044	5966	95	0.016
252	4161.3	4127.1	4182.5	2969	2951	2977	5970	5849	6033	5951	93	0.016
266	4161.9	4127.5	4183.1	2962	2949	2973	5943	5842	6017	5934	88	0.015
280	4162.2	4127.9	4183.3	2959	2948	2970	5931	5839	6006	5925	84	0.014
294	4167.6	4134.8	4188.6	2953	2939	2962	5915	5813	5981	5903	85	0.014
300	4171.0	4136.5	4191.3	2950	2931	2957	5908	5784	5965	5885	93	0.016

*i** means initial reading after 28 days of curing

Table A.44: Mass, frequency, and moduli of elasticity of 50% SL-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4109.4	4128.0	4119.2	2997	2999	2990	6007	6043	5994	6014	25	0.004
14	4093.0	4112.3	4103.1	2954	2957	2942	5813	5852	5780	5815	36	0.006
31	4093.6	4113.8	4104.0	2944	2949	2935	5774	5823	5754	5784	35	0.006
44	4094.8	4115.1	4106.0	2948	2948	2932	5792	5821	5745	5786	38	0.007
59	4094.6	4114.2	4105.1	2948	2952	2943	5792	5835	5787	5804	27	0.005
74	4094.0	4113.6	4105.2	2952	2950	2936	5806	5826	5759	5797	34	0.006
84	4092.9	4112.7	4103.2	2945	2945	2940	5777	5805	5772	5785	18	0.003
98	4092.5	4112.7	4103.3	2947	2952	2936	5785	5833	5757	5791	39	0.007
112	4092.9	4112.5	4103.3	2947	2951	2937	5785	5829	5761	5791	34	0.006
126	4093.2	4112.6	4103.7	2948	2952	2938	5790	5833	5765	5796	34	0.006
140	4093.4	4112.0	4103.8	2950	2952	2938	5798	5832	5765	5798	33	0.006
155	4093.1	4111.8	4103.5	2946	2947	2937	5782	5812	5761	5785	26	0.004
168	4092.5	4111.5	4103.0	2942	2945	2937	5765	5804	5760	5776	24	0.004
183	4091.6	4111.4	4102.7	2939	2943	2935	5752	5796	5752	5767	25	0.004
197	4092.2	4111.8	4103.1	2937	2941	2928	5745	5788	5725	5753	32	0.006
213	4093.6	4113.2	4103.4	2934	2937	2920	5735	5775	5694	5735	40	0.007
225	4093.0	4112.1	4102.9	2935	2933	2915	5738	5757	5674	5723	44	0.008
238	4094.6	4113.6	4104.0	2931	2943	2922	5725	5799	5703	5742	50	0.009
252	4094.1	4113.3	4104.4	2930	2940	2921	5720	5786	5700	5735	45	0.008
266	4093.5	4112.8	4104.8	2931	2937	2919	5723	5774	5692	5730	41	0.007
280	4093.7	4113.0	4105.1	2930	2935	2919	5720	5766	5693	5726	37	0.007
294	4096.8	4116.4	4106.9	2930	2936	2917	5724	5775	5687	5729	44	0.008
300	4100.1	4118.0	4108.6	2927	2936	2917	5717	5777	5690	5728	45	0.008

*i** means initial reading after 28 days of curing

Table A.45: Mass, frequency, and moduli of elasticity of 20% FA-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4086.9	4095.5	4083.6	2970	2972	2973		5867	5888	5874	5876	10	0.002
16	4081.9	4090.3	4078.6	2953	2954	2959		5793	5809	5812	5805	10	0.002
29	4087.8	4096.0	4085.0	2979	2976	2982		5904	5904	5912	5907	5	0.001
44	4087.9	4094.8	4084.2	2997	2996	3005		5976	5982	6002	5987	14	0.002
59	4086.4	4095.2	4082.9	3005	3007	3010		6006	6027	6020	6018	11	0.002
74	4087.2	4095.2	4083.1	3014	3014	3017		6006	6027	6020	6018	11	0.002
84	4087.7	4096.1	4083.8	3020	3021	3028		6068	6084	6094	6082	13	0.002
98	4087.8	4096.3	4083.9	3024	3025	3033		6084	6101	6114	6100	15	0.002
112	4087.9	4096.6	4084.2	3029	3030	3036		6104	6121	6127	6117	12	0.002
126	4088.1	4097.0	4084.6	3034	3035	3041		6125	6142	6148	6138	12	0.002
140	4088.3	4097.2	4085.1	3038	3039	3045		6141	6159	6165	6155	12	0.002
155	4088.6	4097.8	4085.9	3043	3044	3050		6162	6180	6186	6176	13	0.002
168	4088.9	4098.1	4086.5	3045	3046	3051		6170	6188	6191	6183	11	0.002
183	4089.4	4098.4	4087.4	3048	3051	3052		6183	6209	6196	6196	13	0.002
197	4087.8	4097.0	4087.8	3047	3050	3051		6177	6203	6193	6191	13	0.002
213	4088.9	4097.9	4087.3	3048	3047	3051		6182	6192	6192	6189	6	0.001
224	4089.6	4098.8	4087.2	3048	3052	3054		6184	6214	6204	6201	15	0.002
238	4088.4	4099.9	4088.5	3053	3055	3057		6202	6228	6218	6216	13	0.002
253	4089.8	4101.1	4089.9	3057	3054	3056		6220	6225	6217	6221	4	0.001
266	4090.5	4099.5	4091.2	3055	3059	3059		6213	6243	6231	6229	15	0.002
280	4092.6	4098.7	4090.2	3060	3063	3062		6237	6258	6241	6246	11	0.002
294	4092.0	4101.8	4091.3	3063	3060	3064		6248	6251	6251	6250	2	0.000
300	4092.6	4101.7	4090.6	3060	3061	3060		6237	6255	6234	6242	11	0.002

*i** means initial reading after 28 days of curing

Table A.46: Mass, frequency, and moduli of elasticity of 20% FA-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4115.2	4081.9	4100.6	2981	2951	2981	5952	5785	5931	5889	91	0.015
16	4109.6	4076.0	4095.1	2964	2930	2955	5876	5695	5820	5797	93	0.016
29	4114.2	4080.8	4098.8	2976	2943	2968	5930	5752	5876	5853	91	0.016
44	4113.5	4080.0	4098.8	2992	2961	2987	5993	5822	5952	5922	89	0.015
59	4114.1	4080.0	4099.4	2996	2965	2993	6010	5838	5977	5941	91	0.015
74	4114.9	4080.4	4100.3	2998	2968	2995	6019	5850	5986	5952	90	0.015
84	4116.1	4082.7	4102.8	3002	2974	3000	6037	5877	6010	5975	86	0.014
98	4116.3	4082.9	4103.1	3005	2978	3006	6050	5893	6034	5992	86	0.014
112	4116.8	4083.2	4103.1	3009	2985	3009	6066	5921	6046	6011	79	0.013
126	4117.0	4083.6	4103.5	3014	2988	3013	6087	5934	6063	6028	82	0.014
140	4116.1	4083.9	4103.6	3018	2991	3017	6102	5946	6079	6042	84	0.014
155	4116.1	4084.1	4103.7	3022	2995	3018	6118	5962	6083	6055	82	0.013
168	4116.1	4084.5	4103.7	3025	2998	3022	6130	5975	6099	6068	82	0.014
183	4118.1	4084.9	4103.8	3026	2997	3025	6137	5971	6112	6073	89	0.015
197	4120.4	4088.2	4106.4	3026	2990	3018	6141	5948	6087	6059	99	0.016
213	4122.5	4089.3	4107.9	3024	2985	3014	6136	5930	6073	6046	105	0.017
224	4123.0	4089.7	4109.0	3025	2986	3018	6140	5935	6091	6055	107	0.018
238	4123.8	4090.4	4109.5	3029	2988	3020	6158	5944	6100	6067	111	0.018
253	4124.5	4090.9	4110.2	3032	2990	3023	6171	5952	6113	6079	113	0.019
266	4126.2	4092.3	4111.6	3034	2992	3026	6182	5962	6127	6090	114	0.019
280	4125.6	4093.5	4113.6	3037	2995	3029	6193	5976	6143	6104	114	0.019
294	4127.8	4093.2	4112.7	3038	2994	3031	6200	5972	6149	6107	120	0.020
300	4127.1	4093.8	4112.9	3036	2994	3030	6191	5973	6146	6103	115	0.019

*i** means initial reading after 28 days of curing

Table A.47: Mass, frequency, and moduli of elasticity of 20% FA-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3		1	2	3	Average	Std Dev	COV
*i**	4144.8	4115.8	4126.1	2992	2975	2975		6039	5929	5943	5970	60	0.010
16	4130.9	4098.8	4110.0	2941	2932	2915		5815	5735	5684	5745	66	0.012
29	4139.0	4107.2	4118.5	2931	2927	2905		5787	5727	5657	5724	65	0.011
44	4147.2	4115.6	4127.8	2928	2925	2909		5787	5731	5685	5734	51	0.009
59	4157.1	4124.8	4136.6	2916	2910	2893		5753	5685	5635	5691	59	0.010
74	4162.3	4130.4	4142.7	2915	2913	2889		5756	5704	5627	5696	65	0.011
84	4168.5	4137.2	4149.4	2915	2905	2885		5765	5682	5621	5689	72	0.013
98	4170.1	4140.3	4151.2	2910	2900	2881		5747	5667	5608	5674	70	0.012
112	4174.5	4144.5	4154.4	2906	2806	2877		5737	5311	5596	5548	217⁑	0.039
126	4178.2	4147.8	4157.2	2901	2800	2873		5723	5292	5585	5533	220⁑	0.040
140	4180.1	4150.2	4160.1	2896	2795	2869		5706	5277	5573	5518	220⁑	0.040
155	4183.6	4154.3	4164.2	2890	2789	2863		5687	5259	5555	5500	219⁑	0.040
168	4185.8	4158.2	4166.7	2883	2784	2858		5662	5245	5539	5482	214⁑	0.039
183	4186.3	4160.5	4170.0	2874	2874	2853		5628	5593	5524	5582	53	0.009
197	4189.0	4163.7	4173.1	2869	2863	2840		5612	5555	5478	5548	67	0.012
213	4190.7	4164.6	4174.6	2865	2855	2831		5598	5525	5445	5523	77	0.014
224	4193.8	4168.3	4178.2	2853	2849	2831		5556	5506	5450	5504	53	0.010
238	4195.4	4170.4	4179.5	2844	2840	2821		5523	5474	5413	5470	55	0.010
253	4198.1	4173.6	4180.8	2839	2836	2813		5507	5463	5384	5451	62	0.011
266	4201.6	4176.2	4183.7	2830	2829	2804		5477	5440	5354	5423	63	0.012
280	4203.8	4179.0	4185.9	2821	2818	2795		5445	5401	5322	5389	62	0.012
294	4205.3	4180.1	4187.2	2816	2813	2788		5427	5383	5297	5369	66	0.012
300	4207.1	4181.9	4188.6	2811	2807	2785		5410	5363	5287	5354	62	0.012

*i** means initial reading after 28 days of curing

⁑ high values for Std Dev could be due to errors in reading or entering data

Table A.48: Mass, frequency, and moduli of elasticity of 20% FA-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3		1	2	3	Average	Std Dev	COV
*i**	4134.5	4128.7	4111.7	2995	2987	2966		6036	5995	5887	5973	77	0.013
16	4097.1	4092.3	4073.0	2905	2907	2898		5627	5628	5567	5608	35	0.006
29	4100.4	4095.1	4075.7	2900	2902	2878		5612	5613	5494	5573	68	0.012
44	4100.0	4094.9	4074.9	2902	2910	2880		5620	5644	5501	5588	76	0.014
59	4099.2	4095.3	4071.7	2890	2894	2870		5572	5582	5458	5538	69	0.012
74	4097.6	4092.5	4070.8	2885	2894	2865		5551	5578	5438	5522	74	0.013
84	4097.4	4093.4	4069.9	2888	2896	2866		5562	5587	5441	5530	78	0.014
98	4097.5	4093.3	4070.1	2888	2896	2866		5562	5587	5441	5530	78	0.014
112	4097.5	4093.6	4070.3	2887	2895	2865		5558	5584	5438	5527	78	0.014
126	4097.8	4093.8	4070.7	2886	2895	2866		5555	5584	5442	5527	75	0.014
140	4098.1	4094.0	4071.1	2887	2894	2865		5559	5580	5439	5526	76	0.014
155	4098.6	4094.1	4071.3	2888	2894	2865		5564	5581	5439	5528	77	0.014
168	4098.7	4094.2	4071.4	2887	2893	2864		5560	5577	5435	5524	77	0.014
183	4099.0	4094.1	4071.3	2887	2893	2864		5560	5577	5435	5524	77	0.014
197	4101.0	4095.3	4072.6	2884	2886	2860		5551	5551	5422	5508	75	0.014
213	4102.9	4098.1	4075.0	2883	2883	2855		5550	5544	5406	5500	81	0.015
224	4103.1	4098.0	4075.4	2881	2882	2855		5543	5540	5406	5496	78	0.014
238	4103.8	4098.5	4076.3	2882	2881	2855		5548	5537	5408	5497	78	0.014
253	4104.7	4099.2	4077.8	2880	2882	2857		5541	5541	5417	5500	72	0.013
266	4105.4	4100.6	4078.6	2879	2880	2855		5538	5536	5411	5495	73	0.013
280	4106.8	4101.8	4080.5	2880	2877	2851		5544	5526	5398	5489	79	0.014
294	4108.1	4102.7	4080.1	2876	2878	2853		5530	5531	5405	5489	72	0.013
300	4107.8	4102.5	4079.9	2878	2879	2854		5538	5534	5409	5493	74	0.013

*i** means initial reading after 28 days of curing

Table A.49: Mass, frequency, and moduli of elasticity of 35% FA-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4123.9	4124.5	4138.9	2906	2930	2944	5668	5763	5838	5756	85	0.015
16	4120.7	4121.9	4135.9	2916	2942	2957	5703	5806	5886	5798	92	0.016
30	4124.8	4125.8	4140.2	2949	2971	2997	5838	5927	6052	5939	108	0.018
45	4125.3	4125.7	4140.4	2966	2994	3012	5906	6019	6113	6013	104	0.017
56	4125.5	4127.3	4141.8	2973	3000	3025	5935	6046	6168	6049	117	0.019
70	4126.4	4127.8	4142.8	2981	3005	3030	5935	6046	6168	6049	117	0.019
84	4126.7	4128.2	4143.2	2985	3010	3034	5984	6087	6207	6093	112	0.018
99	4127.3	4128.9	4143.8	2988	3014	3039	5997	6104	6229	6110	116	0.019
112	4128.2	4129.2	4144.1	2993	3019	3044	6019	6125	6250	6131	116	0.019
128	4129.6	4130.5	4145.2	2997	3023	3049	6037	6143	6272	6151	118	0.019
140	4130.1	4131.2	4146.0	3002	3027	3053	6058	6161	6289	6169	116	0.019
155	4130.3	4132.1	4147.6	3007	3032	3059	6078	6182	6317	6192	120	0.019
168	4130.9	4132.4	4148.4	3011	3035	3068	6095	6195	6355	6215	131	0.021
183	4130.5	4132.6	4148.2	3012	3036	3070	6099	6199	6363	6220	133	0.021
197	4130.8	4133.1	4148.8	3014	3038	3074	6107	6208	6381	6232	138	0.022
211	4130.6	4132.5	4148.0	3013	3037	3074	6103	6203	6379	6229	140	0.022
224	4130.8	4132.7	4147.9	3014	3032	3073	6107	6183	6375	6222	138	0.022
238	4131.4	4133.1	4148.7	3017	3041	3075	6120	6221	6385	6242	133	0.021
252	4132.0	4133.4	4149.1	3018	3043	3077	6125	6229	6393	6249	135	0.022
266	4132.7	4134.2	4149.7	3021	3045	3078	6138	6239	6399	6259	131	0.021
280	4133.1	4134.9	4150.6	3025	3047	3079	6155	6248	6404	6269	126	0.020
294	4134.2	4136.8	4151.4	3029	3049	3081	6173	6259	6414	6282	122	0.019
300	4134.5	4136.7	4151.2	3030	3049	3080	6178	6259	6409	6282	117	0.019

*i** means initial reading after 28 days of curing

Table A.50: Mass, frequency, and moduli of elasticity of 35% FA-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3		1	2	3	Average	Std Dev	COV
*i**	4154.1	4125.4	4176.7	2965	2945	2960		5944	5823	5956	5908	73	0.012
16	4150.3	4121.1	4171.9	2955	2943	2950		5898	5809	5909	5872	55	0.009
30	4152.6	4123.7	4175.1	2981	2963	2971		6006	5892	5998	5965	63	0.011
45	4154.0	4125.1	4175.9	2982	2972	2980		6012	5930	6035	5992	55	0.009
56	4154.7	4125.4	4177.5	2988	2977	2983		6037	5950	6050	6012	54	0.009
70	4156.0	4126.4	4178.8	2994	2980	2987		6063	5964	6068	6032	59	0.010
84	4157.3	4126.8	4179.5	3000	2984	2992		6089	5981	6089	6053	63	0.010
99	4158.2	4127.6	4180.2	3004	2989	2997		6107	6002	6111	6073	62	0.010
112	4159.6	4128.5	4183.2	3009	2994	3003		6129	6023	6140	6097	65	0.011
128	4161.2	4130.4	4184.6	3015	2999	3006		6156	6046	6154	6119	63	0.010
140	4161.6	4131.8	4185.0	3019	3001	3009		6173	6056	6167	6132	66	0.011
155	4162.2	4132.1	4185.2	3025	3005	3011		6199	6073	6175	6149	67	0.011
168	4162.7	4132.9	4185.1	3030	3009	3016		6220	6090	6196	6169	69	0.011
183	4163.5	4134.2	4186.3	3032	3013	3017		6229	6108	6202	6180	63	0.010
197	4164.3	4135.8	4187.4	3029	3018	3015		6218	6131	6195	6181	45	0.007
211	4166.2	4137.0	4188.8	3028	3016	3018		6217	6125	6209	6184	51	0.008
224	4167.6	4137.4	4189.4	3024	3020	3015		6203	6141	6198	6181	34	0.006
238	4168.9	4138.3	4189.9	3026	3022	3016		6213	6151	6203	6189	33	0.005
252	4169.6	4139.4	4191.1	3029	3025	3018		6226	6165	6213	6201	32	0.005
266	4170.9	4140.2	4192.0	3030	3027	3020		6232	6174	6222	6210	31	0.005
280	4171.8	4141.5	4193.1	3033	3029	3021		6246	6184	6228	6219	32	0.005
294	4173.0	4142.8	4194.2	3036	3028	3023		6260	6182	6238	6227	40	0.006
300	4173.1	4143.1	4194.4	3035	3028	3022		6256	6182	6234	6224	38	0.006

*i** means initial reading after 28 days of curing

Table A.51: Mass, frequency, and moduli of elasticity of 35% FA-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4140.4	4163.2	4123.8	2892	2942	2935	5636	5865	5781	5761	116	0.020
16	4122.5	4145.2	4103.6	2865	2905	2905	5507	5693	5636	5612	95	0.017
30	4130.8	4153.5	4112.0	2870	2916	2908	5538	5748	5659	5648	106	0.019
45	4137.4	4158.8	4118.4	2867	2915	2904	5535	5751	5653	5646	108	0.019
56	4139.6	4159.9	4120.7	2867	2914	2902	5538	5749	5648	5645	106	0.019
70	4144.1	4166.4	4125.1	2866	2911	2906	5540	5746	5670	5652	104	0.018
84	4146.2	4168.6	4126.8	2867	2914	2907	5547	5761	5676	5661	108	0.019
99	4148.6	4170.5	4129.2	2869	2917	2909	5558	5775	5687	5673	110	0.019
112	4150.2	4172.8	4130.5	2870	2921	2910	5564	5795	5693	5684	116	0.020
128	4153.2	4175.2	4133.4	2871	2924	2911	5572	5810	5701	5694	119	0.021
140	4155.8	4177.9	4137.2	2872	2927	2911	5579	5825	5706	5703	123	0.022
155	4158.4	4179.5	4140.6	2874	2931	2912	5590	5844	5714	5716	127	0.022
168	4161.7	4181.8	4144.3	2876	2935	2913	5602	5863	5723	5730	130	0.023
183	4163.6	4183.6	4146.3	2873	2931	2908	5593	5849	5707	5716	128	0.022
197	4165.6	4185.3	4148.4	2869	2928	2903	5580	5840	5690	5703	130	0.023
211	4167.9	4187.4	4150.3	2866	2924	2898	5572	5827	5673	5690	128	0.023
224	4169.3	4189.7	4152.6	2865	2920	2896	5570	5814	5668	5684	123	0.022
238	4171.9	4191.6	4154.3	2866	2922	2896	5577	5825	5671	5691	125	0.022
252	4173.9	4194.0	4155.9	2868	2925	2897	5588	5840	5677	5701	128	0.022
266	4175.5	4196.1	4158.5	2867	2927	2899	5586	5851	5688	5708	134	0.023
280	4178.3	4198.0	4161.2	2865	2926	2903	5582	5849	5707	5713	134	0.023
294	4181.2	4200.4	4163.3	2864	2924	2905	5582	5845	5718	5715	132	0.023
300	4181.1	4200.5	4163.8	2863	2926	2906	5578	5853	5723	5718	138	0.024

*i** means initial reading after 28 days of curing

Table A.52: Mass, frequency, and moduli of elasticity of 35% FA-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4145.4	4157.3	4121.6	2927	2965	2931	5780	5948	5763	5830	102	0.018
16	4103.4	4113.4	4078.5	2867	2905	2867	5489	5650	5456	5532	103	0.019
30	4102.5	4112.7	4078.5	2867	2900	2864	5488	5629	5445	5521	96	0.017
45	4102.6	4111.9	4078.6	2866	2899	2860	5485	5624	5430	5513	100	0.018
56	4101.4	4111.1	4076.7	2865	2898	2863	5479	5619	5438	5512	95	0.017
70	4102.1	4111.2	4077.3	2860	2893	2855	5461	5600	5409	5490	99	0.018
84	4102.5	4111.6	4077.8	2862	2895	2855	5469	5608	5410	5496	102	0.019
99	4103.1	4112.2	4078.1	2865	2897	2857	5481	5617	5418	5505	102	0.018
112	4103.8	4112.9	4078.2	2867	2899	2859	5490	5626	5425	5514	102	0.019
128	4103.9	4113.2	4078.3	2870	2903	2861	5502	5642	5433	5525	106	0.019
140	4103.8	4113.2	4078.2	2873	2907	2863	5513	5657	5440	5537	110	0.020
155	4104.1	4113.7	4078.8	2875	2911	2865	5521	5673	5449	5548	115	0.021
168	4104.4	4113.6	4079.2	2878	2915	2867	5533	5689	5457	5560	118	0.021
183	4104.8	4114.1	4079.5	2876	2914	2866	5526	5686	5454	5555	119	0.021
197	4105.3	4114.5	4079.8	2874	2911	2865	5519	5675	5450	5548	115	0.021
211	4105.8	4114.9	4079.3	2873	2909	2869	5516	5667	5465	5549	105	0.019
224	4106.0	4115.6	4080.2	2871	2906	2867	5508	5657	5458	5541	103	0.019
238	4106.7	4116.2	4080.9	2872	2908	2870	5513	5665	5471	5550	102	0.018
252	4107.3	4116.9	4081.5	2873	2910	2871	5518	5674	5475	5556	105	0.019
266	4107.9	4117.3	4082.3	2872	2912	2869	5515	5682	5469	5555	112	0.020
280	4108.5	4118.1	4083.1	2875	2914	2870	5527	5691	5474	5564	113	0.020
294	4108.1	4118.6	4083.4	2876	2915	2872	5530	5696	5482	5569	112	0.020
300	4108.2	4118.8	4083.2	2876	2913	2871	5530	5688	5478	5565	110	0.020

*i** means initial reading after 28 days of curing

Table A.53: Mass, frequency, and moduli of elasticity of 50% FA-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4153.2	4191.4	4115.9	2896	2932	2877	5669	5864	5545	5693	161	0.028
16	4150.2	4187.9	4113.7	2925	2960	2899	5779	5972	5627	5792	173	0.030
30	4153.6	4190.9	4117.3	2966	2999	2947	5947	6135	5820	5967	158	0.027
45	4156.5	4194.3	4119.0	2990	3025	2970	6048	6247	5913	6069	168	0.028
56	4158.0	4194.5	4120.4	2998	3032	2976	6082	6276	5939	6099	169	0.028
70	4158.5	4195.9	4121.1	3005	3043	2987	6082	6276	5939	6099	169	0.028
84	4159.8	4196.5	4122.1	3011	3051	2992	6138	6358	6006	6167	178	0.029
99	4160.9	4197.2	4122.5	3015	3057	2997	6156	6384	6026	6189	181	0.029
112	4162.4	4198.3	4124.2	3021	3062	3001	6183	6406	6045	6211	182	0.029
126	4164.2	4199.1	4125.4	3028	3069	3005	6214	6437	6063	6238	188	0.030
140	4165.5	4201.1	4127.1	3033	3071	3011	6236	6448	6090	6258	180	0.029
155	4166.6	4201.6	4128.8	3037	3080	3015	6255	6487	6108	6283	191	0.030
168	4167.7	4201.3	4130.4	3041	3087	3019	6273	6516	6127	6305	197	0.031
183	4168.9	4201.0	4132.9	3044	3093	3025	6287	6541	6155	6328	196	0.031
197	4169.5	4201.3	4133.1	3050	3092	3029	6313	6537	6172	6340	184	0.029
210	4168.7	4200.5	4133.5	3056	3089	3031	6336	6523	6180	6347	172	0.027
224	4169.0	4200.7	4133.2	3060	3090	3036	6353	6528	6200	6360	164	0.026
237	4169.7	4201.2	4133.6	3063	3093	3039	6367	6541	6213	6374	164	0.026
253	4170.3	4202.0	4134.3	3067	3096	3041	6384	6555	6222	6387	166	0.026
266	4171.2	4202.5	4134.5	3071	3098	3044	6402	6564	6235	6401	165	0.026
280	4171.9	4203.1	4135.2	3073	3103	3046	6412	6587	6244	6414	171	0.027
294	4172.2	4203.9	4135.5	3075	3107	3047	6421	6605	6249	6425	178	0.028
300	4172.3	4203.7	4135.4	3075	3108	3046	6421	6609	6245	6425	182	0.028

*i** means initial reading after 28 days of curing

Table A.54: Mass, frequency, and moduli of elasticity of 50% FA-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			**Frequency of specimens (Hz)**			**Moduli of elasticity of specimens (ksi)**					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4185.6	4184.3	4151.3	2945	2901	2896	5908	5731	5666	5769	125	0.022
16	4179.7	4178.8	4145.3	2953	2919	2914	5932	5795	5729	5819	104	0.018
30	4180.7	4179.8	4147.0	2986	2943	2939	6067	5892	5830	5930	123	0.021
45	4184.0	4182.4	4149.6	2992	2954	2957	6096	5940	5905	5980	102	0.017
56	4184.6	4182.9	4149.9	2999	2965	2960	6125	5985	5918	6009	106	0.018
70	4185.8	4185.0	4152.0	3004	2965	2965	6148	5988	5941	6025	108	0.018
84	4186.8	4186.3	4153.2	3009	2971	2972	6170	6014	5970	6051	105	0.017
99	4187.9	4187.7	4154.3	3013	2977	2978	6188	6040	5996	6075	100	0.016
112	4189.2	4188.9	4155.4	3018	2983	2982	6210	6066	6014	6097	102	0.017
126	4190.3	4190.1	4156.0	3022	2988	2988	6228	6089	6039	6119	98	0.016
140	4191.5	4191.4	4157.4	3028	2992	2993	6255	6107	6061	6141	101	0.016
155	4192.8	4192.5	4158.6	3032	2997	2996	6273	6129	6075	6159	102	0.017
168	4193.5	4193.4	4159.1	3037	3002	3001	6295	6151	6096	6181	103	0.017
183	4193.3	4194.1	4160.7	3040	3004	3002	6307	6160	6103	6190	106	0.017
197	4194.5	4194.9	4161.6	3039	3000	2998	6305	6145	6088	6179	113	0.018
210	4195.6	4195.6	4162.4	3042	2995	2995	6319	6125	6077	6174	128	0.021
224	4197.0	4196.8	4163.4	3040	2993	2991	6313	6119	6062	6164	131	0.021
237	4197.9	4197.4	4164.0	3042	2995	2994	6322	6128	6075	6175	130	0.021
253	4198.6	4198.3	4164.7	3045	2997	2996	6336	6137	6084	6186	133	0.021
266	4199.4	4199.0	4165.6	3046	3000	2998	6341	6151	6094	6195	130	0.021
280	4200.1	4199.7	4166.3	3047	3004	2999	6346	6168	6099	6204	128	0.021
294	4200.3	4200.6	4167.7	3046	3006	3003	6343	6178	6117	6212	117	0.019
300	4200.2	4200.9	4167.9	3047	3006	3002	6347	6178	6113	6213	121	0.019

*i** means initial reading after 28 days of curing

Table A.55: Mass, frequency, and moduli of elasticity of 50% FA-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4215.2	4204.2	4229.1	2932	2935	2950	5898	5894	5990	5927	54	0.009
16	4209.4	4199.7	4223.6	2908	2910	2928	5793	5788	5893	5825	59	0.010
30	4212.9	4203.9	4227.5	2936	2937	2955	5910	5902	6008	5940	59	0.010
45	4215.6	4206.8	4229.0	2936	2938	2958	5914	5910	6022	5949	64	0.011
56	4215.7	4207.2	4229.9	2933	2937	2957	5902	5906	6019	5943	66	0.011
70	4218.0	4209.7	4232.5	2940	2941	2965	5934	5926	6056	5972	73	0.012
84	4219.3	4211.2	4234.1	2943	2943	2968	5948	5936	6070	5985	74	0.012
99	4220.9	4212.7	4235.4	2945	2946	2971	5958	5950	6085	5998	75	0.013
112	4222.1	4214.0	4236.8	2948	2948	2974	5972	5960	6099	6010	77	0.013
126	4223.7	4215.5	4238.1	2951	2950	2977	5986	5971	6113	6023	78	0.013
140	4225.1	4217.0	4239.3	2953	2954	2981	5996	5989	6131	6039	80	0.013
155	4226.5	4218.2	4240.9	2955	2952	2984	6007	5983	6146	6045	88	0.015
168	4228.0	4219.5	4242.1	2954	2956	2983	6005	6001	6143	6050	81	0.013
183	4227.8	4219.5	4243.4	2957	2959	2986	6016	6013	6158	6062	83	0.014
197	4228.9	4220.7	4244.7	2952	2953	2978	5998	5990	6127	6038	77	0.013
210	4229.8	4222.0	4246.1	2946	2948	2969	5975	5972	6092	6013	68	0.011
224	4231.1	4223.2	4247.5	2942	2944	2964	5960	5957	6073	5997	66	0.011
237	4233.2	4225.0	4249.0	2940	2942	2961	5955	5952	6063	5990	63	0.011
253	4235.0	4227.1	4250.3	2937	2939	2957	5945	5942	6049	5979	60	0.010
266	4236.7	4228.9	4251.6	2935	2937	2953	5940	5937	6034	5970	55	0.009
280	4238.0	4230.6	4253.4	2932	2934	2950	5929	5927	6024	5960	55	0.009
294	4240.5	4232.1	4255.4	2929	2930	2949	5921	5913	6023	5952	61	0.010
300	4240.8	4232.2	4255.4	2930	2931	2948	5925	5917	6019	5954	57	0.009

*i** means initial reading after 28 days of curing

Table A.56: Mass, frequency, and moduli of elasticity of 50% FA-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4170.6	4145.0	4187.4	2920	2872	2880	5787	5564	5653	5668	112	0.020
16	4121.7	4096.9	4137.4	2871	2830	2837	5529	5340	5420	5430	95	0.017
30	4119.9	4095.0	4136.3	2876	2830	2847	5546	5338	5456	5447	105	0.019
45	4120.3	4095.2	4135.8	2875	2830	2837	5543	5338	5418	5433	103	0.019
56	4119.3	4094.6	4135.7	2876	2833	2841	5545	5348	5433	5442	99	0.018
70	4118.7	4094.1	4135.4	2870	2828	2833	5521	5329	5402	5417	97	0.018
84	4119.2	4094.5	4135.7	2875	2832	2836	5541	5345	5414	5433	100	0.018
99	4119.5	4094.9	4136.2	2878	2836	2841	5553	5360	5433	5449	97	0.018
112	4120.0	4095.2	4136.6	2883	2839	2845	5573	5372	5449	5465	102	0.019
126	4120.4	4095.5	4137.2	2889	2843	2847	5597	5388	5458	5481	107	0.019
140	4121.0	4096.0	4137.6	2892	2845	2851	5610	5396	5474	5493	108	0.020
155	4121.4	4096.2	4138.2	2896	2848	2855	5626	5407	5490	5508	110	0.020
168	4121.9	4096.7	4138.8	2900	2851	2858	5642	5419	5502	5521	112	0.020
183	4121.5	4097.6	4138.3	2906	2853	2860	5665	5428	5509	5534	120	0.022
197	4120.8	4097.1	4138.8	2904	2854	2856	5656	5431	5494	5527	116	0.021
210	4121.4	4097.8	4138.2	2900	2856	2854	5641	5440	5486	5522	105	0.019
224	4121.0	4097.4	4138.0	2896	2855	2853	5625	5436	5482	5514	99	0.018
237	4121.8	4098.2	4138.8	2894	2853	2853	5618	5429	5483	5510	98	0.018
253	4122.5	4099.1	4139.6	2893	2850	2851	5615	5419	5476	5503	101	0.018
266	4123.2	4100.5	4140.4	2892	2847	2852	5613	5409	5481	5501	103	0.019
280	4124.0	4100.9	4141.3	2890	2845	2854	5606	5402	5490	5499	102	0.019
294	4124.8	4101.1	4141.9	2892	2843	2849	5615	5395	5472	5494	112	0.020
300	4124.9	4101.0	4141.7	2891	2844	2850	5611	5399	5475	5495	108	0.020

*i** means initial reading after 28 days of curing

Table A.57: Mass, frequency, and moduli of elasticity of Control-RE-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3		1	2	3	Average	Std Dev	COV
*i**	4080.7	4142.8	4141.2	2933	2944	2932		5713	5844	5794	5784	66	0.011
14	4083.0	4144.3	4143.8	2947	2958	2947		5517	5613	5572	5567	48	0.009
28	4085.4	4145.5	4147.5	2964	2972	2964		5841	5959	5930	5910	61	0.010
42	4084.9	4145.1	4146.8	2971	2978	2972		5868	5983	5961	5937	61	0.010
56	4084.4	4144.9	4146.2	2979	2985	2981		5899	6011	5997	5969	61	0.010
70	4085.1	4145.3	4146.9	2985	2992	2989		5924	6040	6030	5998	64	0.011
84	4084.6	4144.8	4145.1	2992	3000	2997		5951	6071	6059	6027	66	0.011
98	4084.7	4144.1	4143.9	3002	3009	3005		5991	6107	6090	6063	62	0.010
112	4084.1	---⁑	4143.6	3005	---⁑	3007		6002	---⁑	6098	6050	68	0.011
126	4084.5	---⁑	4143.5	3009	---⁑	3008		6019	---⁑	6102	6060	59	0.010
140	4085.7	---⁑	4144.1	3013	---⁑	3014		6037	---⁑	6127	6082	64	0.011
150	4086.2	---⁑	4144.9	3016	---⁑	3019		6049	---⁑	6148	6099	70	0.011

*i** means initial reading after 28 days of curing
⁑ specimen no. 2 is damaged in handling

Table A.58: Mass, frequency, and moduli of elasticity of Control-RE-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3		1	2	3	Average	Std Dev	COV
*i**	4146.6	4113.7	4173.8	2969	2937	2980		5949	5775	6032	5919	131	0.022
14	4148.4	4114.7	4175.8	2966	2943	2979		5939	5800	6031	5924	116	0.020
28	4150.4	4116.1	4178.4	2965	2950	2980		5938	5830	6039	5936	105	0.018
42	4150.1	4116.3	4178.1	2970	2954	2984		5958	5846	6055	5953	105	0.018
56	4149.4	4116.6	4177.6	2976	2957	2988		5981	5858	6070	5970	106	0.018
70	4148.8	4115.8	4177.1	2981	2960	2992		6000	5869	6086	5985	109	0.018
84	4147.5	4117.1	4176.8	2986	2964	2996		6019	5887	6102	6002	108	0.018
98	4146.1	4117.7	4176.3	2990	2971	3002		6033	5915	6125	6025	105	0.017
112	4145.8	4117.1	4176.0	2991	2967	3005		6036	5899	6137	6024	120	0.020
126	4146.3	4118.0	4176.6	2993	2968	3006		6045	5904	6142	6030	120	0.020
140	4146.9	4119.2	4177.4	2998	2971	3009		6066	5918	6156	6046	120	0.020
150	4147.3	4120.7	4179.8	3001	2976	3012		6079	5940	6172	6063	117	0.019

*i** means initial reading after 28 days of curing

Table A.59: Mass, frequency, and moduli of elasticity of Control-RE-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4136.1	4167.2	4116.5	2960	2975	2928	5898	6003	5744	5881	130	0.022
14	4143.2	4174.6	4124.5	2907	2925	2862	5698	5813	5498	5670	159	0.028
28	4149.0	4179.3	4130.9	2853	2883	2800	5496	5654	5271	5474	192	0.035
42	4137.5	4166.2	4114.4	2837	2865	2780	5420	5566	5175	5387	197	0.037
56	4125.4	4151.9	4096.8	2820	2846	2758	5339	5473	5072	5295	204	0.039
70	4114.3	4137.8	4080.4	2780	2800	2715	5175	5280	4895	5117	199	0.039
84	4103.4	4124.3	4063.2	2762	2782	2689	5095	5195	4782	5024	216	0.043
98	4093.0	4108.3	4043.0	2742	2761	2664	5008	5097	4670	4925	225	0.046
112	4075.6	4085.6	4025.3	2718	2726	2635	4900	4941	4549	4797	216	0.045
126	4035.6	4058.2	3988.7	2670	2681	2610	4682	4747	4422	4617	172	0.037
140	3996.5	4002.9	3948.5	2614	2629	2573	4444	4503	4254	4401	130	0.030
150	3944.6	3939.5	3880.8	2564	2580	2514	4221	4268	3992	4160	148	0.035

*i** means initial reading after 28 days of curing

Table A.60: Mass, frequency, and moduli of elasticity of Control-RE-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	1	2	3	1	2	3	1	2	3	Average	Std Dev	COV
*i**	4114.5	4103.9	4116.5	2960	2946	2947	5867	5797	5819	5828	36	0.006
14	4102.8	4093.2	4105.6	2947	2936	2940	5799	5743	5776	5772	28	0.005
28	4089.9	4081.0	4091.9	2936	2931	2933	5738	5706	5729	5724	16	0.003
42	4090.8	4081.7	4093.1	2935	2931	2931	5735	5707	5723	5722	14	0.002
56	4091.9	4082.5	4094.0	2933	2930	2930	5729	5704	5720	5718	13	0.002
70	4092.7	4083.2	4095.2	2927	2922	2921	5707	5674	5687	5689	16	0.003
84	4093.6	4083.9	4096.1	2920	2916	2917	5681	5652	5672	5668	15	0.003
98	4094.5	4084.7	4097.4	2911	2908	2910	5647	5622	5647	5639	15	0.003
112	4094.2	4084.2	4097.3	2905	2904	2906	5623	5606	5631	5620	13	0.002
126	4095.2	4083.4	4098.0	2898	2895	2899	5598	5570	5605	5591	19	0.003
140	4094.0	4082.4	4097.9	2889	2891	2890	5561	5553	5570	5562	9	0.002
150	4092.5	4080.9	4096.6	2880	2884	2881	5525	5524	5534	5528	6	0.001

*i** means initial reading after 28 days of curing

Table A.61: Mass, frequency, and moduli of elasticity of 50% SL-RE-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4102.9	4071.2	4062.0	2933	2939	2884		5744	5723	5499	5655	136	0.024
14	4108.2	4075.3	4068.5	2913	2915	2871		5423	5383	5160	5322	142	0.027
28	4110.4	4078.7	4070.4	2925	2926	2881		5724	5683	5499	5635	120	0.021
43	4112.1	4080.8	4072.7	2933	2933	2886		5757	5713	5521	5664	126	0.022
56	4113.7	4083.2	4074.9	2940	2941	2892		5787	5748	5547	5694	129	0.023
70	4115.2	4085.6	4076.8	2949	2948	2898		5825	5779	5572	5725	134	0.023
84	4116.7	4087.8	4078.8	2957	2955	2907		5858	5809	5610	5759	132	0.023
98	4118.8	4090.3	4081.3	2964	2965	2915		5889	5852	5644	5795	132	0.023
112	4119.1	4091.2	4082.7	2972	2969	2922		5921	5869	5673	5821	131	0.022
126	4120.5	4092.8	4083.4	2981	2975	2931		5959	5896	5709	5855	130	0.022
140	4120.9	4093.4	4084.1	2988	2983	2940		5988	5928	5745	5887	126	0.021
150	4121.6	4094.0	4085.6	2993	2990	2948		6009	5957	5779	5915	121	0.020

*i** means initial reading after 28 days of curing

Table A.62: Mass, frequency, and moduli of elasticity of 50% SL-RE-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)				Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**		**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4098.7	4064.5	4079.9	2982	2925	2942		5932	5660	5747	5780	139	0.024
14	4100.3	4066.8	4082.6	2954	2898	2904		5823	5559	5603	5662	142	0.025
28	4106.1	4071.3	4086.5	2963	2905	2918		5867	5592	5663	5707	143	0.025
43	4107.2	4072.5	4087.8	2969	2910	2922		5892	5613	5680	5729	146	0.025
56	4108.4	4074.1	4089.2	2974	2916	2925		5914	5638	5694	5749	146	0.025
70	4110.0	4075.1	4090.7	2978	2921	2931		5932	5659	5719	5770	144	0.025
84	4111.1	4076.2	4091.8	2984	2925	2936		5958	5676	5741	5791	148	0.025
98	4111.8	4076.6	4092.8	2991	2930	2939		5987	5696	5754	5812	154	0.026
112	4113.2	4078.5	4095.1	2991	2933	2942		5989	5710	5769	5823	147	0.025
126	4114.4	4080.3	4096.6	2994	2939	2946		6003	5736	5786	5842	142	0.024
140	4114.9	4081.1	4097.2	2996	2941	2945		6011	5745	5783	5847	144	0.025
150	4115.3	4082.4	4097.9	2998	2944	2948		6020	5759	5796	5858	141	0.024

*i** means initial reading after 28 days of curing

Table A.63: Mass, frequency, and moduli of elasticity of 50% SL-RE-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4047.9	4073.4	4092.5	2893	2936	2931	5514	5715	5722	5650	118	0.021
14	4052.8	4077.4	4096.5	2875	2922	2923	5452	5666	5696	5605	133	0.024
28	4059.8	4085.3	4103.9	2865	2916	2915	5424	5654	5675	5584	140	0.025
43	4061.1	4086.7	4105.4	2869	2917	2915	5440	5659	5678	5592	132	0.024
56	4062.5	4088.2	4107.0	2875	2919	2916	5465	5669	5684	5606	122	0.022
70	4064.1	4089.3	4108.7	2878	2918	2918	5479	5667	5694	5613	117	0.021
84	4065.5	4091.2	4110.5	2882	2920	2918	5496	5677	5696	5623	111	0.020
98	4066.2	4091.8	4111.2	2887	2922	2919	5516	5686	5701	5634	103	0.018
112	4067.7	4092.3	4112.5	2884	2917	2918	5506	5667	5699	5624	103	0.018
126	4067.9	4093.0	4112.8	2883	2914	2918	5503	5656	5699	5620	103	0.018
140	4066.8	4093.5	4112.4	2880	2909	2911	5490	5638	5672	5600	97	0.017
150	4067.5	4094.2	4112.1	2875	2899	2905	5472	5600	5648	5573	91	0.016

*i** means initial reading after 28 days of curing

Table A.64: Mass, frequency, and moduli of elasticity of 50% SL-RE-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4083.8	4048.4	4109.5	2935	2915	2925	5725	5599	5722	5682	72	0.013
14	4072.1	4034.5	4095.3	2901	2864	2876	5578	5386	5513	5492	97	0.018
28	4073.6	4038.3	4098.2	2895	2860	2873	5557	5376	5505	5479	93	0.017
43	4073.0	4037.5	4098.6	2897	2864	2876	5563	5390	5517	5490	90	0.016
56	4072.9	4038.5	4097.8	2900	2869	2880	5575	5410	5532	5506	85	0.016
70	4073.1	4037.4	4098.1	2899	2871	2882	5571	5416	5540	5509	82	0.015
84	4073.9	4037.9	4098.6	2903	2876	2884	5588	5436	5548	5524	79	0.014
98	4073.7	4036.9	4098.5	2905	2880	2885	5595	5450	5552	5532	75	0.014
112	4073.0	4036.5	4097.5	2896	2874	2883	5560	5426	5543	5510	73	0.013
126	4073.4	4036.6	4096.8	2890	2870	2880	5537	5411	5530	5493	71	0.013
140	4074.2	4037.0	4097.2	2886	2864	2873	5523	5389	5504	5472	72	0.013
150	4075.4	4037.7	4097.9	2884	2859	2867	5517	5371	5482	5457	76	0.014

*i** means initial reading after 28 days of curing

Table A.65: Mass, frequency, and moduli of elasticity of 50% FA-RE-0.44 specimens exposed to deionized water

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4136.7	4164.7	4103.2	2886	2873	2845	5608	5595	5405	5536	113	0.020
14	4131.5	4160.4	4098.2	2887	2885	2850	5232	5232	5043	5169	109	0.021
28	4135.7	4164.1	4103.0	2930	2925	2899	5778	5798	5612	5730	102	0.018
42	4136.5	4165.0	4104.1	2945	2938	2910	5839	5851	5656	5782	109	0.019
56	4137.4	4165.7	4105.0	2961	2950	2924	5904	5900	5712	5839	110	0.019
70	4138.5	4166.5	4106.3	2975	2962	2935	5961	5949	5757	5889	115	0.019
84	4138.9	4167.4	4107.6	2992	2978	2947	6030	6015	5806	5950	125	0.021
98	4139.8	4168.3	4108.2	3007	2990	2966	6092	6065	5882	6013	114	0.019
112	4140.1	4168.8	4108.1	3010	2997	2971	6105	6094	5902	6034	114	0.019
126	4140.5	4169.9	4107.8	3014	3005	2974	6122	6128	5913	6054	122	0.020
140	4140.9	4170.1	4107.9	3015	3003	2973	6126	6120	5909	6052	124	0.020
150	4140.8	4170.3	4108.4	3016	3007	2974	6130	6137	5914	6060	127	0.021

*i** means initial reading after 28 days of curing

Table A.66: Mass, frequency, and moduli of elasticity of 50% FA-RE-0.44 specimens exposed to NaCl solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4133.9	4142.7	4107.3	2894	2850	2875	5635	5476	5525	5546	81	0.015
14	4132.5	4141.9	4105.8	2896	2870	2879	5641	5553	5539	5577	55	0.010
28	4134.5	4143.8	4108.3	2930	2895	2907	5777	5652	5650	5693	72	0.013
42	4135.7	4145.3	4109.4	2938	2902	2914	5810	5682	5679	5724	75	0.013
56	4136.9	4146.7	4110.3	2947	2910	2922	5847	5715	5712	5758	77	0.013
70	4138.7	4148.0	4111.4	2955	2916	2929	5882	5740	5741	5788	82	0.014
84	4139.2	4149.1	4112.8	2964	2922	2936	5918	5766	5770	5818	87	0.015
98	4140.1	4150.8	4113.8	2971	2930	2942	5948	5800	5795	5847	87	0.015
112	4140.8	4151.0	4114.3	2975	2940	2946	5965	5839	5811	5872	82	0.014
126	4141.1	4151.3	4115.2	2981	2949	2952	5989	5876	5836	5900	79	0.013
140	4141.5	4151.9	4114.9	2985	2951	2955	6006	5885	5848	5913	83	0.014
150	4142.0	4152.3	4115.5	2988	2955	2954	6019	5901	5845	5922	89	0.015

*i** means initial reading after 28 days of curing

Table A.67: Mass, frequency, and moduli of elasticity of 50% FA-RE-0.44 specimens exposed to $CaCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4144.4	4132.0	4159.4	2880	2844	2866	5595	5439	5560	5531	82	0.015
14	4151.6	4142.9	4166.8	2855	2826	2841	5507	5385	5474	5455	63	0.012
28	4155.6	4147.5	4171.7	2885	2853	2870	5629	5494	5592	5572	70	0.013
42	4157.3	4149.6	4173.6	2892	2859	2878	5659	5520	5626	5602	72	0.013
56	4159.4	4152.0	4175.9	2900	2866	2888	5693	5551	5669	5637	76	0.014
70	4161.0	4153.9	4178.0	2908	2873	2896	5727	5580	5703	5670	79	0.014
84	4162.9	4156.5	4180.3	2915	2882	2903	5757	5619	5734	5703	74	0.013
98	4164.2	4157.6	4181.7	2922	2889	2909	5787	5648	5759	5731	74	0.013
112	4164.8	4157.8	4182.3	2922	2888	2911	5787	5644	5768	5733	78	0.014
126	4165.1	4158.2	4182.6	2924	2890	2911	5796	5652	5768	5739	76	0.013
140	4164.7	4157.8	4182.9	2925	2892	2912	5799	5660	5773	5744	74	0.013
150	4165.2	4158.1	4182.6	2927	2893	2914	5808	5664	5780	5751	76	0.013

*i** means initial reading after 28 days of curing

Table A.68: Mass, frequency, and moduli of elasticity of 50% FA-RE-0.44 specimens exposed to $MgCl_2$ solution

	Mass of specimens (g)			Frequency of specimens (Hz)			Moduli of elasticity of specimens (ksi)					
Cycles	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**Average**	**Std Dev**	**COV**
*i**	4108.8	4125.1	4128.9	2873	2875	2887	5520	5549	5601	5557	41	0.007
14	4063.8	4078.4	4082.9	2824	2841	2836	5275	5357	5345	5326	45	0.008
28	4062.6	4077.7	4082.3	2832	2843	2849	5303	5364	5393	5353	46	0.009
42	4062.4	4077.5	4082.9	2833	2846	2852	5306	5375	5405	5362	51	0.009
56	4062.9	4077.9	4082.5	2831	2849	2856	5300	5387	5420	5369	62	0.012
70	4063.3	4078.4	4082.8	2832	2853	2858	5304	5403	5428	5378	65	0.012
84	4062.8	4078.6	4083.5	2829	2852	2860	5292	5399	5436	5376	75	0.014
98	4063.0	4078.7	4083.3	2830	2859	2863	5296	5426	5447	5390	82	0.015
112	4062.8	4078.5	4082.9	2828	2855	2857	5288	5411	5424	5374	75	0.014
126	4062.3	4078.0	4082.2	2825	2854	2853	5276	5406	5408	5363	75	0.014
140	4062.7	4078.5	4082.0	2826	2858	2850	5281	5422	5396	5366	75	0.014
150	4063.1	4078.3	4083.4	2822	2856	2852	5266	5414	5406	5362	83	0.015

*i** means initial reading after 28 days of curing

Table A.69: Relative dynamic modulus of elasticity at 300 cycles

	Exposure Solution											
	DI Water			NaCl			$CaCl_2$			$MgCl_2$		
	1	2	3	1	2	3	1	2	3	1	2	3
Control-0.38	1.05	1.04	1.06	1.00	1.02	1.03	0.70	0.66	0.68	0.85	0.85	0.86
20% SL-0.38	1.05	1.06	1.06	1.03	1.03	1.03	0.89	0.89	0.89	0.95	0.96	0.96
35% SL-0.38	1.05	1.04	1.05	1.03	1.02	1.04	0.97	0.97	0.96	0.97	0.97	0.97
50% SL-0.38	1.05	1.05	1.06	1.03	1.03	1.04	0.99	0.98	0.99	0.98	0.98	0.98
20% FA-0.38	1.06	1.06	1.06	1.03	1.02	1.02	0.91	0.92	0.92	0.96	0.96	0.96
35% FA-0.38	1.07	1.07	1.07	1.03	1.04	1.04	0.96	0.97	0.97	0.94	0.95	0.95
50% FA-0.38	1.07	1.09	1.08	1.05	1.06	1.05	1.00	1.00	1.00	0.96	0.96	0.96
Control-0.44	1.06	1.06	1.06	1.04	1.03	1.03	0.52	0.52	0.53	0.85	0.83	0.86
20% SL-0.44	1.05	1.04	1.04	1.03	1.03	1.03	0.86	0.87	0.88	0.95	0.95	0.94
35% SL-0.44	1.05	1.05	1.05	1.03	1.03	1.02	0.94	0.93	0.94	0.94	0.95	0.95
50% SL-0.44	1.04	1.04	1.04	1.02	1.02	1.02	0.96	0.97	0.97	0.95	0.96	0.95
20% FA-0.44	1.06	1.06	1.06	1.04	1.03	1.04	0.90	0.90	0.89	0.92	0.92	0.92
35% FA-0.44	1.09	1.09	1.10	1.05	1.06	1.05	0.99	1.00	0.99	0.96	0.96	0.95
50% FA-0.44	1.13	1.13	1.13	1.07	1.08	1.08	1.00	1.00	1.00	0.97	0.97	0.97

Table A.70: Student's t-test results displaying statistical significance of differences in relative dynamic modulus for mixtures exposed to $CaCl_2$ solution

Mixture	Average relative dynamic modulus	Control-0.38	20% SL-0.38	35% SL-0.38	50% SL-0.38	20% FA-0.38	35% FA-0.38	50% FA-0.38	Control-0.44	20% SL-0.44	35% SL-0.44	50% SL-0.44	20% FA-0.44	35% FA-0.44	50% FA-0.44
		0.68	0.89	0.97	0.99	0.92	0.97	1.00	0.53	0.87	0.94	0.96	0.90	0.99	1.00
Control-0.38	0.68		4.5E-05	1.4E-05	1.1E-05	3.5E-05	1.3E-05	8.4E-06	1.9E-04	8.3E-05	2.3E-05	1.4E-05	5.0E-05	9.9E-06	7.6E-06
20% SL-0.38	0.89			2.7E-05	1.3E-05	5.3E-03	6.6E-06	1.0E-06	9.2E-08	6.9E-03	3.0E-04	2.9E-05	2.9E-01	7.7E-06	6.5E-07
35% SL-0.38	0.97				1.1E-02	6.9E-04	4.9E-01	7.3E-04	7.0E-08	3.5E-05	3.2E-03	4.3E-01	1.6E-04	4.1E-03	2.7E-04
50% SL-0.38	0.99					2.1E-04	3.0E-03	4.0E-02	6.3E-08	1.8E-05	5.0E-04	5.6E-03	6.8E-05	3.0E-01	5.4E-03
20% FA-0.38	0.92						4.8E-04	6.1E-05	2.6E-07	1.1E-03	2.0E-02	8.7E-04	2.7E-02	1.4E-04	4.1E-05
35% FA-0.38	0.97							3.4E-05	3.2E-08	1.9E-05	2.1E-03	7.3E-01	1.1E-04	9.8E-04	9.4E-06
50% FA-0.38	1.00								2.0E-08	5.6E-06	9.2E-05	3.9E-04	2.2E-05	1.8E-01	7.0E-04
Control-0.44	0.53									3.4E-07	1.3E-07	6.7E-08	3.1E-07	5.0E-08	1.8E-08
20% SL-0.44	0.87										1.8E-04	3.8E-05	8.1E-03	1.3E-05	4.2E-06
35% SL-0.44	0.94											4.9E-03	1.6E-03	2.9E-04	5.3E-05
50% SL-0.44	0.96												1.9E-04	2.2E-03	1.6E-04
20% FA-0.44	0.90													4.8E-05	1.6E-05
35% FA-0.44	0.99														1.2E-02
50% FA-0.44	1.00														

Red shading indicates that the differences are statistically significant

Table A.71: Student's t-test results displaying statistical significance of differences in relative dynamic modulus for mixtures exposed to $MgCl_2$ solution

Mixture	Average relative dynamic modulus	Control-0.38	20% SL-0.38	35% SL-0.38	50% SL-0.38	20% FA-0.38	35% FA-0.38	50% FA-0.38	Control-0.44	20% SL-0.44	35% SL-0.44	50% SL-0.44	20% FA-0.44	35% FA-0.44	50% FA-0.44
		0.86	0.96	0.97	0.98	0.96	0.95	0.96	0.85	0.94	0.95	0.95	0.92	0.95	0.97
Control-0.38	0.86		6.7E-06	4.9E-06	4.3E-06	5.7E-06	2.0E-05	4.3E-06	5.1E-01	3.2E-05	2.0E-05	1.3E-05	5.7E-05	1.2E-05	3.7E-06
20% SL-0.38	0.96			1.3E-03	2.9E-04	4.9E-02	8.8E-03	7.5E-04	1.9E-04	9.9E-03	2.4E-02	1.4E-01	4.5E-05	4.6E-01	1.9E-04
35% SL-0.38	0.97				7.8E-03	3.2E-03	7.3E-04	3.5E-02	1.3E-04	1.1E-03	1.3E-03	2.3E-03	2.1E-05	4.1E-03	5.6E-01
50% SL-0.38	0.98					4.4E-04	2.5E-04	1.1E-03	9.6E-05	3.7E-04	3.9E-04	5.2E-04	1.6E-05	7.4E-04	5.5E-03
20% FA-0.38	0.96						3.3E-03	2.0E-03	1.7E-04	4.4E-03	7.8E-03	2.8E-02	2.8E-05	8.2E-02	2.9E-04
35% FA-0.38	0.95							8.7E-04	3.3E-04	5.6E-01	5.0E-01	7.0E-02	7.9E-04	3.3E-02	4.0E-04
50% FA-0.38	0.96								1.4E-04	1.4E-03	1.8E-03	3.6E-03	1.3E-05	7.5E-03	5.8E-04
Control-0.44	0.85									3.9E-04	3.0E-04	2.4E-04	1.0E-03	2.2E-04	1.2E-04
20% SL-0.44	0.94										2.7E-01	5.0E-02	2.1E-03	2.7E-02	7.0E-04
35% SL-0.44	0.95											1.9E-01	8.3E-02	8.3E-02	7.5E-04
50% SL-0.44	0.95												2.4E-04	4.8E-01	1.1E-03
20% FA-0.44	0.92													1.9E-04	9.7E-06
35% FA-0.44	0.95														1.9E-03
50% FA-0.44	0.97														

Red shading indicates that the differences are statistically significant

APPENDIX B: VISUAL INSPECTIONS FOR SPECIMENS EXPOSED TO DEIONIZED WATER AT 300 CYCLES OF WETTING AND DRYING

(a) Control (100% portland cement, 0% slag cement)

(b) 20% slag

(c) 35% slag

(d) 50% slag

Figure B.1: Specimens for concrete mixtures with *w/cm* of 0.38 containing slag cement exposed to DI water at 300 cycles

(a) Control (100% portland cement, 0% fly ash)

(b) 20% fly

(c) 35% fly

(d) 50% fly

Figure B.2: Specimens for concrete mixtures with *w/cm* of 0.38 containing fly ash exposed to DI water at 300 cycles

(a) Control (100% portland cement, 0% slag cement)

(b) 20% slag

(c) 35% slag

(d) 50% slag

Figure B.3: Specimens for concrete mixtures with *w/cm* of 0.44 containing slag cement exposed to DI water at 300 cycles

(a) Control (100% portland cement, 0% fly ash) (b) 20% fly (c) 35% fly (d) 50% fly

Figure B.4: Specimens for concrete mixtures with *w/cm* of 0.44 containing fly ash exposed to DI water at 300 cycles

APPENDIX C: SCALING DATA FOR MIXTURES IN CHAPTER 3

For mixtures in the following tables: slag cement (SL), Class C fly ash (FA), 0.38 and 0.44 represent the *w/cm* ratios, exposure to NaCl (NaCl), exposure to $CaCl_2$ ($CaCl_2$), 14 and 28 represent the days of curing.

Table C.1: Scaling test results for mixtures

Mixture: Control-0.38-NaCl-14

Specimen Number	Effective Area in²	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
1	70.4	0.8	3.76E-03	0.8	3.76E-03	0.4	1.88E-03	0.6	2.82E-03
2	70.3	1.0	4.70E-03	0.7	3.29E-03	0.6	2.82E-03	0.7	3.29E-03
3	68.7	1.1	5.29E-03	0.6	2.89E-03	0.5	2.41E-03	0.6	2.89E-03
Average			4.58E-03		3.31E-03		2.37E-03		3.00E-03
Cumulative mass loss (lb/ft²)			4.58E-03		7.90E-03		1.03E-02		1.33E-02

Mixture: Control-0.38-NaCl-28

Specimen Number	Effective Area in²	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
1	67.7	0.9	4.39E-03	0.7	3.42E-03	0.7	3.42E-03	0.4	1.95E-03
2	69.5	0.8	3.81E-03	0.6	2.85E-03	0.4	1.90E-03	0.3	1.43E-03
3	72.0	0.6	2.75E-03	0.9	4.13E-03	0.6	2.75E-03	0.5	2.30E-03
Average			3.65E-03		3.47E-03		2.69E-03		1.89E-03
Cumulative mass loss (lb/ft²)			3.65E-03		7.12E-03		9.81E-03		1.17E-02

Mixture: Control-0.38-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.0	1.2	5.75E-03	1.6	7.67E-03	0.9	4.31E-03	0.7	3.35E-03
2	69.2	1.0	4.78E-03	1.5	7.17E-03	0.8	3.82E-03	0.8	3.82E-03
3	68.1	0.9	4.37E-03	1.9	9.22E-03	1.2	5.83E-03	1.3	6.31E-03
Average			4.97E-03		8.02E-03		4.65E-03		4.50E-03
Cumulative mass loss (lb/ft^2)			4.97E-03		1.30E-02		1.76E-02		2.21E-02

Mixture: Control-0.38- $CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	68.3	0.9	4.36E-03	0.7	3.39E-03	0.8	3.87E-03	0.5	2.42E-03
2	68.3	1.1	5.32E-03	1.3	6.29E-03	0.7	3.39E-03	0.6	2.90E-03
3	68.5	0.8	3.86E-03	1.3	6.27E-03	0.9	4.34E-03	0.4	1.93E-03
Average			4.51E-03		5.32E-03		3.87E-03		2.42E-03
Cumulative mass loss (lb/ft^2)			4.51E-03		9.83E-03		1.37E-02		1.61E-02

Mixture: 20% SL–0.38- NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	67.7	1.4	6.84E-03	1.1	5.37E-03	0.9	4.39E-03	0.8	3.91E-03
2	68.6	1.3	6.26E-03	1.4	6.75E-03	1.1	5.30E-03	1.0	4.82E-03
3	68.9	0.8	3.84E-03	1.0	4.80E-03	1.1	5.28E-03	1.2	5.76E-03
Average			5.65E-03		5.64E-03		4.99E-03		4.83E-03
Cumulative mass loss (lb/ft^2)			5.65E-03		1.13E-02		1.63E-02		2.11E-02

Mixture: 20% SL-0.38- NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	67.6	2.3	1.12E-02	1.0	4.89E-03	0.7	3.42E-03	1.1	5.38E-03
2	71.8	2.9	1.34E-02	1.3	5.99E-03	1.0	4.60E-03	0.7	3.22E-03
3	68.6	2.9	1.40E-02	0.8	3.86E-03	1.1	5.30E-03	1.6	7.71E-03
Average			1.29E-02		4.91E-03		4.44E-03		5.44E-03
Cumulative mass loss (lb/ft^2)			1.29E-02		1.78E-02		2.22E-02		2.76E-02

Mixture: 20% SL-0.38-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	68.9	5.4	2.59E-02	1.6	7.68E-03	0.6	2.88E-03	0.5	2.40E-03
2	68.8	4.3	2.07E-02	2.0	9.61E-03	0.3	1.44E-03	0.7	3.36E-03
3	70.1	5.2	2.45E-02	1.8	8.49E-03	0.7	3.30E-03	0.8	3.77E-03
Average			2.37E-02		8.59E-03		2.54E-03		3.18E-03
Cumulative mass loss (lb/ft^2)			2.37E-02		3.23E-02		3.48E-02		3.80E-02

Mixture: 20% SL-0.38-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	68.8	4.8	2.31E-02	1.3	6.25E-03	1.2	5.77E-03	0.6	2.88E-03
2	71.0	3.9	1.82E-02	1.7	7.92E-03	1.5	6.98E-03	0.7	3.26E-03
3	69.0	4.3	2.06E-02	1.5	7.19E-03	1.3	6.23E-03	0.5	2.40E-03
Average			2.06E-02		7.12E-03		6.33E-03		2.85E-03
Cumulative mass loss (lb/ft^2)			2.06E-02		2.77E-02		3.41E-02		3.69E-02

Mixture: 20% FA-0.38- NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	72.3	1.2	5.49E-03	1.1	5.03E-03	0.9	4.12E-03	1.2	5.49E-03
2	72.4	1.5	6.85E-03	1.3	5.94E-03	0.6	2.74E-03	1.4	6.39E-03
3	69.7	1.0	4.74E-03	0.9	4.27E-03	0.7	3.32E-03	1.6	7.59E-03
Average			5.69E-03		5.08E-03		3.39E-03		6.49E-03
Cumulative mass loss (lb/ft^2)			5.69E-03		1.08E-02		1.42E-02		2.07E-02

Mixture: 20% FA-0.38-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.0	1.1	5.27E-03	1.2	5.75E-03	1.2	5.75E-03	0.8	3.83E-03
2	68.8	1.6	7.69E-03	1.6	7.69E-03	1.0	4.81E-03	0.5	2.40E-03
3	69.1	1.7	8.13E-03	2.2	1.05E-02	0.8	3.83E-03	0.6	2.87E-03
Average			7.03E-03		7.99E-03		4.79E-03		3.04E-03
Cumulative mass loss (lb/ft^2)			7.03E-03		1.50E-02		1.98E-02		2.28E-02

Mixture: 20% FA-0.38- $CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.3	1.2	5.72E-03	1.6	7.63E-03	1.1	5.25E-03	0.9	4.29E-03
2	67.3	1.6	7.86E-03	1.0	4.91E-03	0.8	3.93E-03	1.2	5.89E-03
3	71.0	1.3	6.05E-03	1.4	6.52E-03	0.9	4.19E-03	1.0	4.66E-03
Average			6.55E-03		6.35E-03		4.46E-03		4.95E-03
Cumulative mass loss (lb/ft^2)			6.55E-03		1.29E-02		1.74E-02		2.23E-02

Mixture: 20% FA-0.38-$CaCl_2$-28

Specimen Number	Effective Area in²	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
1	69.6	1.1	5.22E-03	0.8	3.80E-03	1.1	5.22E-03	0.7	3.32E-03
2	66.9	1.3	6.42E-03	1.2	5.93E-03	0.9	4.45E-03	0.5	2.47E-03
3	68.8	1.2	5.77E-03	1.1	5.29E-03	0.8	3.84E-03	0.4	1.92E-03
Average			5.80E-03		5.01E-03		4.51E-03		2.57E-03
Cumulative mass loss (lb/ft²)			5.80E-03		1.08E-02		1.53E-02		1.79E-02

Mixture: Control-0.44-NaCl-14

Specimen Number	Effective Area in²	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
1	71.1	1.2	5.58E-03	1.3	6.04E-03	0.9	4.18E-03	0.7	3.25E-03
2	70.4	1.0	4.70E-03	1.1	5.17E-03	0.4	1.88E-03	0.6	2.82E-03
3	72.4	1.3	5.94E-03	1.4	6.39E-03	0.8	3.65E-03	0.8	3.65E-03
Average			5.40E-03		5.87E-03		3.24E-03		3.24E-03
Cumulative mass loss (lb/ft²)			5.40E-03		1.13E-02		1.45E-02		1.78E-02

Mixture: Control-0.44-NaCl-28

Specimen Number	Effective Area in²	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
1	70.0	1.0	4.72E-03	1.3	6.14E-03	0.8	3.78E-03	0.4	1.89E-03
2	72.8	0.9	4.09E-03	1.2	5.45E-03	1.0	4.54E-03	1.0	4.54E-03
3	68.5	1.2	5.79E-03	1.8	8.69E-03	0.8	3.86E-03	0.8	3.86E-03
Average			4.87E-03		6.76E-03		4.06E-03		3.43E-03
Cumulative mass loss (lb/ft²)			4.87E-03		1.16E-02		1.57E-02		1.91E-02

Mixture: Control-0.44-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.0	1.1	5.27E-03	2.5	1.20E-02	3.3	1.58E-02	4.5	2.16E-02
2	68.5	0.9	4.34E-03	1.9	9.17E-03	2.0	9.65E-03	2.7	1.30E-02
3	70.3	1.1	5.17E-03	2.1	9.88E-03	1.4	6.58E-03	1.7	7.99E-03
Average			4.93E-03		1.03E-02		1.07E-02		1.42E-02
Cumulative mass loss (lb/ft^2)			4.93E-03		1.53E-02		2.60E-02		4.01E-02

Mixture: Control-0.44-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.3	1.4	6.68E-03	1.4	6.68E-03	1.2	5.72E-03	1.7	8.11E-03
2	68.8	0.6	2.88E-03	1.6	7.69E-03	2.2	1.06E-02	3.4	1.63E-02
3	72.9	1.0	4.53E-03	1.3	5.90E-03	2.3	1.04E-02	4.9	2.22E-02
Average			4.70E-03		6.75E-03		8.91E-03		1.56E-02
Cumulative mass loss (lb/ft^2)			4.70E-03		1.15E-02		2.04E-02		3.59E-02

Mixture: Control-0.44-RE-NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	71.8	1.6	7.37E-03	1.4	6.45E-03	0.5	2.30E-03	0.3	1.38E-03
2	71.5	1.5	6.94E-03	1.3	6.01E-03	0.3	1.39E-03	0.3	1.39E-03
3	71.0	1.4	6.52E-03	1.3	6.05E-03	0.6	2.79E-03	0.6	2.79E-03
Average			6.94E-03		6.17E-03		2.16E-03		1.85E-03
Cumulative mass loss (lb/ft^2)			6.94E-03		1.31E-02		1.53E-02		1.71E-02

Mixture: Control-0.44-RE-NaCl- 28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.3	0.7	3.29E-03	1.3	6.11E-03	1.3	6.11E-03	0.9	4.23E-03
2	70.0	1.0	4.72E-03	1.0	4.72E-03	1.2	5.67E-03	0.9	4.25E-03
3	69.6	1.5	7.12E-03	2.3	1.09E-02	1.1	5.22E-03	0.8	3.80E-03
Average			5.05E-03		7.25E-03		5.67E-03		4.09E-03
Cumulative mass loss (lb/ft^2)			5.05E-03		1.23E-02		1.80E-02		2.21E-02

Mixture: Control-RE-0.44- $CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.6	1.2	5.70E-03	2.2	1.04E-02	2.6	1.23E-02	1.6	7.60E-03
2	71.1	1.0	4.65E-03	2.9	1.35E-02	3.5	1.63E-02	3.7	1.72E-02
3	69.8	1.2	5.68E-03	2.6	1.23E-02	2.3	1.09E-02	2.6	1.23E-02
Average			5.34E-03		1.21E-02		1.32E-02		1.24E-02
Cumulative mass loss (lb/ft^2)			5.34E-03		1.74E-02		3.06E-02		4.30E-02

Mixture: Control-RE-0.44-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.0	1.3	6.14E-03	1.9	8.97E-03	2.6	1.23E-02	4.0	1.89E-02
2	68.6	1.5	7.23E-03	1.6	7.71E-03	3.1	1.49E-02	2.3	1.11E-02
3	70.3	1.3	6.11E-03	2.6	1.22E-02	3.8	1.79E-02	3.5	1.65E-02
Average			6.49E-03		9.64E-03		1.50E-02		1.55E-02
Cumulative mass loss (lb/ft^2)			6.49E-03		1.61E-02		3.12E-02		4.66E-02

Mixture: 20% SL-0.44-NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	67.1	1.1	5.42E-03	1.5	7.39E-03	0.9	4.43E-03	1.3	6.40E-03
2	71.2	1.9	8.82E-03	2.3	1.07E-02	0.9	4.18E-03	1.5	6.96E-03
3	68.4	2.1	1.01E-02	2.0	9.67E-03	0.6	2.90E-03	1.4	6.77E-03
Average			8.13E-03		9.25E-03		3.84E-03		6.71E-03
Cumulative mass loss (lb/ft^2)			8.13E-03		1.74E-02		2.12E-02		2.79E-02

Mixture: 20% SL-0.44-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	71.2	3.5	1.63E-02	1.2	5.57E-03	0.8	3.71E-03	1.9	8.82E-03
2	69.7	4.5	2.13E-02	1.4	6.64E-03	0.7	3.32E-03	1.5	7.11E-03
3	69.2	3.3	1.58E-02	1.3	6.21E-03	0.9	4.30E-03	1.8	8.60E-03
Average			1.78E-02		6.14E-03		3.78E-03		8.18E-03
Cumulative mass loss (lb/ft^2)			1.78E-02		2.39E-02		2.77E-02		3.59E-02

Mixture: 20% SL-0.44-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.1	4.9	2.34E-02	1.5	7.18E-03	0.3	1.44E-03	1.0	4.78E-03
2	71.1	6.1	2.84E-02	2.8	1.30E-02	0.4	1.86E-03	1.4	6.51E-03
3	69.6	7.6	3.61E-02	2.8	1.33E-02	1.0	4.75E-03	1.0	4.75E-03
Average			2.93E-02		1.12E-02		2.68E-03		5.35E-03
Cumulative mass loss (lb/ft^2)			2.93E-02		4.05E-02		4.31E-02		4.85E-02

Mixture: 20% SL-0.44-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	72.6	4.9	2.23E-02	1.1	5.01E-03	0.5	2.28E-03	1.6	7.29E-03
2	73.4	4.6	2.07E-02	1.6	7.21E-03	0.7	3.15E-03	1.9	8.56E-03
3	69.3	5.7	2.72E-02	1.3	6.20E-03	0.5	2.39E-03	1.4	6.68E-03
Average			2.34E-02		6.14E-03		2.60E-03		7.51E-03
Cumulative mass loss (lb/ft^2)			2.34E-02		2.95E-02		3.22E-02		3.97E-02

Mixture: 35% SL-0.44-NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	72.3	3.0	1.37E-02	1.7	7.77E-03	2.2	1.01E-02	5.6	2.56E-02
2	68.8	4.9	2.35E-02	2.3	1.11E-02	2.3	1.11E-02	4.9	2.35E-02
3	69.6	4.0	1.90E-02	3.1	1.47E-02	1.6	7.60E-03	3.6	1.71E-02
Average			1.88E-02		1.12E-02		9.57E-03		2.21E-02
Cumulative mass loss (lb/ft^2)			1.88E-02		2.99E-02		3.95E-02		6.16E-02

Mixture: 35% SL-0.44-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	67.6	4.7	2.30E-02	4.9	2.40E-02	2.9	1.42E-02	3.0	1.47E-02
2	67.6	6.5	3.18E-02	5.0	2.45E-02	2.4	1.17E-02	2.0	9.78E-03
3	68.5	4.6	2.22E-02	4.9	2.36E-02	2.3	1.11E-02	2.4	1.16E-02
Average			2.57E-02		2.40E-02		1.23E-02		1.20E-02
Cumulative mass loss (lb/ft^2)			2.57E-02		4.97E-02		6.20E-02		7.40E-02

Mixture: 35% SL-0.44-$CaCl_2$-14

Specimen Number	Effective Area in²	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
1	69.3	5.5	2.62E-02	1.4	6.68E-03	0.7	3.34E-03	1.1	5.25E-03
2	69.7	4.1	1.94E-02	1.2	5.69E-03	0.5	2.37E-03	1.1	5.22E-03
3	71.6	3.5	1.62E-02	0.7	3.23E-03	0.6	2.77E-03	0.7	3.23E-03
Average			2.06E-02		5.20E-03		2.83E-03		4.57E-03
Cumulative mass loss (lb/ft²)			2.06E-02		2.58E-02		2.86E-02		3.32E-02

Mixture: 35% SL-0.44-$CaCl_2$-28

Specimen Number	Effective Area in²	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
1	68.6	1.5	7.23E-03	1.0	4.82E-03	0.4	1.93E-03	0.9	4.34E-03
2	67.4	4.0	1.96E-02	3.1	1.52E-02	0.8	3.92E-03	1.1	5.40E-03
3	68.7	3.5	1.68E-02	2.8	1.35E-02	1.0	4.81E-03	0.9	4.33E-03
Average			1.46E-02		1.12E-02		3.55E-03		4.69E-03
Cumulative mass loss (lb/ft²)			1.46E-02		2.57E-02		2.93E-02		3.40E-02

Mixture: 50% SL-0.44-NaCl-14

Specimen Number	Effective Area in²	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft²	g	lb/ft²	g	lb/ft²	g	lb/ft²
1	67.0	10.1	4.98E-02	11.4	5.62E-02	14.3	7.06E-02	4.6	2.27E-02
2	68.5	12.8	6.18E-02	9.7	4.68E-02	10.8	5.21E-02	5.0	2.41E-02
3	68.8	10.9	5.24E-02	14.5	6.97E-02	12.3	5.91E-02	4.5	2.16E-02
Average			5.47E-02		5.76E-02		6.06E-02		2.28E-02
Cumulative mass loss (lb/ft²)			5.47E-02		1.12E-01		1.73E-01		1.96E-01

Mixture: 50% SL-0.44-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.3	29.5	1.39E-01	13.1	6.16E-02	1.6	7.52E-03	0.6	2.82E-03
2	69.7	22.2	1.05E-01	7.4	3.51E-02	1.3	6.17E-03	1.2	5.69E-03
3	70.3	24.7	1.16E-01	10.1	4.75E-02	1.2	5.64E-03	0.9	4.23E-03
Average			1.20E-01		4.81E-02		6.44E-03		4.25E-03
Cumulative mass loss (lb/ft^2)			1.20E-01		1.68E-01		1.75E-01		1.79E-01

Mixture: 50% SL-0.44-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.6	6.1	2.86E-02	3.5	1.64E-02	2.4	1.12E-02	5.2	2.43E-02
2	67.4	6.9	3.38E-02	4.7	2.31E-02	3.8	1.86E-02	4.1	2.01E-02
3	71.5	7.2	3.33E-02	7.6	3.51E-02	4.3	1.99E-02	3.8	1.76E-02
Average			3.19E-02		2.49E-02		1.66E-02		2.07E-02
Cumulative mass loss (lb/ft^2)			3.19E-02		5.68E-02		7.33E-02		9.40E-02

Mixture: 50% SL-0.44-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.6	8.8	4.18E-02	10.6	5.03E-02	1.4	6.65E-03	0.6	2.85E-03
2	69.4	7.4	3.52E-02	6.6	3.14E-02	1.3	6.19E-03	0.6	2.86E-03
3	68.0	5.7	2.77E-02	6.1	2.97E-02	1.8	8.75E-03	0.7	3.40E-03
Average			3.49E-02		3.71E-02		7.20E-03		3.04E-03
Cumulative mass loss (lb/ft^2)			3.49E-02		7.21E-02		7.93E-02		8.23E-02

Mixture: 50% SL-0.44-RE-NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.9	9.4	4.45E-02	10.7	5.06E-02	11.2	5.30E-02	5.2	2.46E-02
2	67.9	11.3	5.50E-02	13.3	6.48E-02	9.8	4.77E-02	6.8	3.31E-02
3	67.9	10.0	4.87E-02	12.1	5.89E-02	10.9	5.31E-02	5.6	2.73E-02
Average			4.94E-02		5.81E-02		5.13E-02		2.83E-02
Cumulative mass loss (lb/ft^2)			4.94E-02		1.07E-01		1.59E-01		1.87E-01

Mixture: 50% SL-0.44-RE-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.3	14.2	6.77E-02	13.8	6.58E-02	3.0	1.43E-02	1.2	5.72E-03
2	67.7	17.4	8.50E-02	10.8	5.27E-02	2.8	1.37E-02	1.3	6.35E-03
3	67.8	14.6	7.12E-02	11.4	5.56E-02	3.8	1.85E-02	2.1	1.02E-02
Average			7.46E-02		5.81E-02		1.55E-02		7.44E-03
Cumulative mass loss (lb/ft^2)			7.46E-02		1.33E-01		1.48E-01		1.56E-01

Mixture: 50% SL-0.44-RE-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	71.3	5.2	2.41E-02	5.4	2.50E-02	3.1	1.44E-02	6.5	3.01E-02
2	68.3	7.4	3.58E-02	6.6	3.19E-02	4.4	2.13E-02	5.4	2.61E-02
3	71.0	9.3	4.33E-02	4.5	2.10E-02	4.2	1.96E-02	5.8	2.70E-02
Average			3.44E-02		2.60E-02		1.84E-02		2.78E-02
Cumulative mass loss (lb/ft^2)			3.44E-02		6.04E-02		7.88E-02		1.07E-01

Mixture: 50% SL-0.44-RE-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.6	9.8	4.65E-02	7.1	3.37E-02	2.4	1.14E-02	1.1	5.22E-03
2	69.0	8.8	4.22E-02	9.1	4.36E-02	2.9	1.39E-02	1.2	5.75E-03
3	69.3	9.3	4.44E-02	8.4	4.01E-02	1.8	8.59E-03	1.2	5.72E-03
Average			4.44E-02		3.91E-02		1.13E-02		5.57E-03
Cumulative mass loss (lb/ft^2)			4.44E-02		8.35E-02		9.48E-02		1.00E-01

Mixture: 20% FA-0.44-NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.6	1.6	7.60E-03	2.0	9.50E-03	1.4	6.65E-03	1.3	6.17E-03
2	70.3	1.3	6.11E-03	1.8	8.46E-03	1.0	4.70E-03	1.2	5.64E-03
3	66.7	1.3	6.44E-03	1.9	9.42E-03	1.9	9.42E-03	1.8	8.92E-03
Average			6.72E-03		9.13E-03		6.92E-03		6.91E-03
Cumulative mass loss (lb/ft^2)			6.72E-03		1.58E-02		2.28E-02		2.97E-02

Mixture: 20% FA-0.44-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	68.6	1.4	6.75E-03	1.9	9.16E-03	2.0	9.64E-03	1.1	5.30E-03
2	68.8	1.9	9.13E-03	1.9	9.13E-03	1.5	7.21E-03	0.9	4.32E-03
3	71.1	1.7	7.90E-03	2.5	1.16E-02	1.3	6.04E-03	0.6	2.79E-03
Average			7.93E-03		9.97E-03		7.63E-03		4.14E-03
Cumulative mass loss (lb/ft^2)			7.93E-03		1.79E-02		2.55E-02		2.97E-02

Mixture: 20% FA-0.44-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.5	2.0	9.38E-03	1.8	8.44E-03	1.1	5.16E-03	1.4	6.56E-03
2	69.0	1.2	5.75E-03	1.7	8.14E-03	1.4	6.71E-03	1.4	6.71E-03
3	69.2	1.5	7.17E-03	1.5	7.17E-03	1.7	8.12E-03	1.3	6.21E-03
Average			7.43E-03		7.92E-03		6.66E-03		6.49E-03
Cumulative mass loss (lb/ft^2)			7.43E-03		1.53E-02		2.20E-02		2.85E-02

Mixture: 20% FA-0.44-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	71.5	1.4	6.47E-03	2.1	9.71E-03	1.0	4.62E-03	0.8	3.70E-03
2	69.4	0.9	4.29E-03	1.6	7.62E-03	1.5	7.15E-03	0.9	4.29E-03
3	68.6	0.9	4.34E-03	1.4	6.75E-03	1.1	5.30E-03	0.6	2.89E-03
Average			5.03E-03		8.03E-03		5.69E-03		3.63E-03
Cumulative mass loss (lb/ft^2)			5.03E-03		1.31E-02		1.87E-02		2.24E-02

Mixture: 35% FA-0.44-NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	68.1	4.5	2.18E-02	2.1	1.02E-02	3.2	1.55E-02	1.7	8.25E-03
2	68.9	4.0	1.92E-02	1.8	8.64E-03	1.5	7.20E-03	2.3	1.10E-02
3	69.6	2.0	9.50E-03	2.1	9.97E-03	1.9	9.02E-03	2.4	1.14E-02
Average			1.68E-02		9.60E-03		1.06E-02		1.02E-02
Cumulative mass loss (lb/ft^2)			1.68E-02		2.64E-02		3.70E-02		4.73E-02

Mixture: 35% FA-0.44-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	72.0	4.2	1.93E-02	3.3	1.52E-02	1.6	7.35E-03	1.2	5.51E-03
2	71.8	2.9	1.34E-02	3.0	1.38E-02	1.4	6.45E-03	1.7	7.83E-03
3	71.8	6.2	2.85E-02	4.4	2.03E-02	1.7	7.83E-03	1.6	7.37E-03
Average			2.04E-02		1.64E-02		7.21E-03		6.90E-03
Cumulative mass loss (lb/ft^2)			2.04E-02		3.68E-02		4.40E-02		5.09E-02

Mixture: 35% FA-0.44-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.8	2.4	1.12E-02	1.6	7.47E-03	1.1	5.14E-03	1.3	6.07E-03
2	68.0	1.6	7.78E-03	0.9	4.38E-03	1.7	8.26E-03	1.4	6.81E-03
3	73.1	2.4	1.09E-02	1.3	5.88E-03	1.0	4.52E-03	1.3	5.88E-03
Average			9.95E-03		5.91E-03		5.97E-03		6.25E-03
Cumulative mass loss (lb/ft^2)			9.95E-03		1.59E-02		2.18E-02		2.81E-02

Mixture: 35% FA-0.44-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	72.1	3.1	1.42E-02	2.0	9.17E-03	1.3	5.96E-03	1.2	5.50E-03
2	73.1	4.3	1.94E-02	3.7	1.67E-02	1.6	7.24E-03	2.1	9.50E-03
3	71.5	3.0	1.39E-02	2.2	1.02E-02	1.3	6.01E-03	1.9	8.78E-03
Average			1.58E-02		1.20E-02		6.40E-03		7.93E-03
Cumulative mass loss (lb/ft^2)			1.58E-02		2.79E-02		3.43E-02		4.22E-02

Mixture: 50% FA-0.44-NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.0	11.0	5.19E-02	6.4	3.02E-02	7.2	3.40E-02	11.7	5.53E-02
2	67.8	8.4	4.10E-02	5.8	2.83E-02	2.7	1.32E-02	7.8	3.80E-02
3	70.5	12.6	5.91E-02	6.4	3.00E-02	5.4	2.53E-02	7.2	3.38E-02
Average			5.07E-02		2.95E-02		2.42E-02		4.23E-02
Cumulative mass loss (lb/ft^2)			5.07E-02		8.02E-02		1.04E-01		1.47E-01

Mixture: 50% FA-0.44-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	65.8	32.7	1.64E-01	18.7	9.40E-02	6.4	3.22E-02	5.1	2.56E-02
2	71.1	30.7	1.43E-01	11.8	5.49E-02	5.7	2.65E-02	6.2	2.88E-02
3	68.7	25.1	1.21E-01	11.2	5.39E-02	6.1	2.94E-02	5.2	2.50E-02
Average			1.43E-01		6.76E-02		2.93E-02		2.65E-02
Cumulative mass loss (lb/ft^2)			1.43E-01		2.10E-01		2.40E-01		2.66E-01

Mixture: 50% FA-0.44-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	68.9	8.3	3.98E-02	2.3	1.10E-02	1.3	6.24E-03	1.3	6.24E-03
2	69.6	6.4	3.04E-02	2.8	1.33E-02	1.1	5.22E-03	1.0	4.75E-03
3	72.1	7.5	3.44E-02	2.6	1.19E-02	1.5	6.88E-03	0.8	3.67E-03
Average			3.49E-02		1.21E-02		6.11E-03		4.89E-03
Cumulative mass loss (lb/ft^2)			3.49E-02		4.70E-02		5.31E-02		5.80E-02

Mixture: 50% FA-0.44-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.2	12.0	5.65E-02	3.1	1.46E-02	0.2	9.42E-04	3.6	1.70E-02
2	69.2	7.9	3.77E-02	2.9	1.39E-02	0.6	2.87E-03	3.2	1.53E-02
3	69.9	11.1	5.25E-02	2.2	1.04E-02	1.2	5.68E-03	5.2	2.46E-02
Average			4.89E-02		1.30E-02		3.16E-03		1.89E-02
Cumulative mass loss (lb/ft^2)			4.89E-02		6.19E-02		6.50E-02		8.40E-02

Mixture: 50% FA-0.44-RE-NaCl-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.5	8.5	3.99E-02	12.6	5.91E-02	6.4	3.00E-02	8.2	3.85E-02
2	69.1	2.1	1.00E-02	6.1	2.92E-02	10.0	4.78E-02	10.0	4.78E-02
3	67.4	7.6	3.73E-02	10.0	4.90E-02	7.5	3.68E-02	7.5	3.68E-02
Average			2.91E-02		4.58E-02		3.82E-02		4.10E-02
Cumulative mass loss (lb/ft^2)			2.91E-02		7.48E-02		1.13E-01		1.54E-01

Mixture: 50% FA-0.44-RE-NaCl-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.3	17.1	8.16E-02	15.3	7.30E-02	7.5	3.58E-02	6.8	3.24E-02
2	69.4	9.8	4.67E-02	10.3	4.91E-02	7.9	3.76E-02	8.4	4.00E-02
3	68.5	10.4	5.02E-02	14.8	7.14E-02	10.2	4.92E-02	9.7	4.68E-02
Average			5.95E-02		6.45E-02		4.09E-02		3.98E-02
Cumulative mass loss (lb/ft^2)			5.95E-02		1.24E-01		1.65E-01		2.05E-01

Mixture: 50% FA-0.44-RE-$CaCl_2$-14

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	69.2	3.9	1.86E-02	1.6	7.64E-03	1.7	8.12E-03	0.9	4.30E-03
2	68.3	7.7	3.73E-02	3.7	1.79E-02	0.9	4.36E-03	1.7	8.23E-03
3	68.3	5.0	2.42E-02	3.0	1.45E-02	1.2	5.81E-03	0.8	3.87E-03
Average			2.67E-02		1.34E-02		6.10E-03		5.47E-03
Cumulative mass loss (lb/ft^2)			2.67E-02		4.01E-02		4.62E-02		5.16E-02

Mixture: 50% FA-0.44-RE-$CaCl_2$-28

Specimen Number	Effective Area in^2	Mass loss at 7 days		Mass loss at 21 days		Mass loss at 35 days		Mass loss at 56 days	
		g	lb/ft^2	g	lb/ft^2	g	lb/ft^2	g	lb/ft^2
1	70.2	7.4	3.48E-02	5.7	2.68E-02	3.6	1.70E-02	2.9	1.37E-02
2	68.3	5.2	2.52E-02	2.6	1.26E-02	2.3	1.11E-02	1.4	6.78E-03
3	66.6	1.8	8.93E-03	3.2	1.59E-02	3.6	1.79E-02	2.3	1.14E-02
Average			2.30E-02		1.84E-02		1.53E-02		1.06E-02
Cumulative mass loss (lb/ft^2)			2.30E-02		4.14E-02		5.67E-02		6.74E-02

Table C.2a: Student's t-test results showing statistical significance (*p*-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	Control–0.38-NaCl-14	Control–0.38-NaCl-28	Control–0.38-$CaCl_2$-14	Control–0.38-$CaCl_2$-28	20% SL-0.38-NaCl-14	20% SL-0.38-NaCl-28	20% SL-0.38-$CaCl_2$-14	20% SL-0.38-$CaCl_2$-28	20% FA-0.38-NaCl-14	20% FA-0.38-NaCl-28	20% FA-0.38-$CaCl_2$-14	20% FA-0.38-$CaCl_2$-28
		0.013	0.012	0.022	0.016	0.021	0.028	0.038	0.037	0.021	0.023	0.022	0.018
Control–0.38-NaCl-14	0.013												
Control–0.38-NaCl-28	0.012	2.2E-01											
Control–0.38-$CaCl_2$-14	0.022	1.0E-02	7.4E-03										
Control–0.38-$CaCl_2$-28	0.016	8.6E-02	3.9E-02	5.0E-02									
20% SL-0.38-NaCl-14	0.021	2.7E-03	2.6E-03	6.5E-01	3.1E-02								
20% SL-0.38-NaCl-28	0.028	1.3E-03	1.2E-03	9.5E-02	4.9E-03	3.1E-02							
20% SL-0.38-$CaCl_2$-14	0.038	1.0E-04	1.2E-04	2.6E-03	3.1E-04	7.6E-04	1.0E-02						
20% SL-0.38-$CaCl_2$-28	0.037	7.1E-06	2.0E-05	1.6E-03	7.6E-05	1.8E-04	6.8E-03	5.2E-01					
20% FA-0.38-NaCl-14	0.021	9.7E-04	1.4E-03	4.9E-01	2.5E-02	7.3E-01	1.9E-02	4.4E-04	4.3E-05				
20% FA-0.38-NaCl-28	0.023	3.0E-03	2.6E-03	7.7E-01	2.0E-02	3.7E-01	9.5E-02	1.8E-03	7.1E-04	2.2E-01			
20% FA-0.38-$CaCl_2$-14	0.022	2.3E-04	5.1E-04	9.3E-01	6.9E-03	3.5E-01	4.0E-02	5.6E-04	3.3E-05	1.0E-01	7.3E-01		
20% FA-0.38-$CaCl_2$-28	0.018	7.1E-03	6.2E-03	1.0E-01	2.5E-01	6.5E-02	6.4E-03	2.7E-04	3.0E-05	4.6E-02	3.4E-02	6.6E-03	

Red shading indicates that the differences are statistically significant

Table C.2b: Student's t-test results showing statistical significance (*p*-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	Control–0.44-NaCl-14	Control–0.44-NaCl-28	Control–0.44-RE-NaCl-14	Control–0.44-RE-NaCl-28	20% SL-0.44-NaCl-14	20% SL-0.44-NaCl-28	35% SL-0.44-NaCl-14	35% SL-0.44-NaCl-28	50% SL-0.44-NaCl-14	50% SL-0.44-NaCl-28	50% SL-0.44-RE-NaCl-14	50% SL-0.44-RE-NaCl-28
		0.018	0.019	0.017	0.022	0.028	0.036	0.062	0.074	0.196	0.179	0.187	0.156
Control–0.44-NaCl-14	0.018												
Control–0.44-NaCl-28	0.019	5.9E-01											
Control–0.44-RE-NaCl-14	0.017	7.4E-01	3.3E-01										
Control–0.44-RE-NaCl-28	0.022	2.2E-01	3.8E-01	1.3E-01									
20% SL-0.44-NaCl-14	0.028	2.0E-02	3.2E-02	9.2E-03	1.5E-01								
20% SL-0.44-NaCl-28	0.036	9.1E-04	1.3E-03	2.2E-04	8.0E-03	3.4E-02							
35% SL-0.44-NaCl-14	0.062	4.5E-04	5.2E-04	3.4E-04	9.9E-04	1.6E-03	3.1E-03						
35% SL-0.44-NaCl-28	0.074	6.3E-05	7.2E-05	3.9E-05	1.6E-04	2.0E-04	2.4E-04	5.9E-02					
50% SL-0.44-NaCl-14	0.196	6.4E-06	6.7E-06	5.6E-06	8.7E-06	9.2E-06	9.3E-06	3.7E-05	3.9E-05				
50% SL-0.44-NaCl-28	0.179	7.2E-04	7.4E-04	7.0E-04	8.1E-04	9.3E-04	1.1E-03	2.6E-03	3.8E-03	4.0E-01			
50% SL-0.44-RE-NaCl-14	0.187	3.3E-05	3.4E-05	3.0E-05	4.0E-05	4.5E-05	5.0E-05	1.5E-04	1.9E-04	4.2E-01	6.9E-01		
50% SL-0.44-RE-NaCl-28	0.156	2.6E-07	2.9E-07	5.8E-08	1.1E-06	8.3E-07	2.6E-07	1.9E-05	1.1E-05	2.0E-03	2.5E-01	1.8E-02	

Red shading indicates that the differences are statistically significant

Table C.2c: Student's t-test results showing statistical significance (p-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	Control–0.44-NaCl-14	Control–0.44-NaCl-28	Control–0.44-RE-NaCl-14	Control–0.44-RE-NaCl-28	20% FA-0.44-NaCl-14	20% FA-0.44-NaCl-28	35% FA-0.44-NaCl-14	35% FA-0.44-NaCl-28	50% FA-0.44-NaCl-14	50% FA-0.44-NaCl-28	50% FA-0.44-RE-NaCl-14	50% FA-0.44-RE-NaCl-28
		0.018	0.019	0.017	0.022	0.030	0.030	0.047	0.051	0.147	0.266	0.154	0.205
Control–0.44-NaCl-14	0.018												
Control–0.44-NaCl-28	0.019	5.9E-01											
Control–0.44-RE-NaCl-14	0.017	7.4E-01	3.3E-01										
Control–0.44-RE-NaCl-28	0.022	2.2E-01	3.8E-01	1.3E-01									
20% FA-0.44-NaCl-14	0.030	1.9E-02	2.8E-02	1.1E-02	1.1E-01								
20% FA-0.44-NaCl-28	0.030	2.5E-03	4.3E-03	2.6E-04	4.3E-02	1.0E+00							
35% FA-0.44-NaCl-14	0.047	3.8E-03	4.6E-03	3.0E-03	8.7E-03	3.0E-02	2.0E-02						
35% FA-0.44-NaCl-28	0.051	8.8E-03	1.0E-02	7.6E-03	1.6E-02	4.3E-02	3.5E-02	6.8E-01					
50% FA-0.44-NaCl-14	0.147	9.7E-04	1.0E-03	9.3E-04	1.1E-03	1.5E-03	1.4E-03	3.0E-03	4.1E-03				
50% FA-0.44-NaCl-28	0.266	6.7E-04	6.9E-04	6.6E-04	7.3E-04	8.2E-04	8.1E-04	1.2E-03	1.3E-03	1.6E-02			
50% FA-0.44-RE-NaCl-14	0.154	1.6E-04	1.7E-04	1.6E-04	2.0E-04	2.6E-04	2.3E-04	6.0E-04	9.8E-04	7.0E-01	1.6E-02		
50% FA-0.44-RE-NaCl-28	0.205	2.9E-04	3.0E-04	2.8E-04	3.3E-04	3.9E-04	3.7E-04	6.6E-04	8.5E-04	5.5E-02	1.1E-01	5.3E-02	

Red shading indicates that the differences are statistically significant

Table C.2d: Student's t-test results showing statistical significance (*p*-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	Control–0.44-$CaCl_2$-14	Control–0.44-$CaCl_2$-28	Control–0.44-RE-$CaCl_2$-14	Control–0.44-RE-$CaCl_2$-28	20% SL-0.44-$CaCl_2$-14	20% SL-0.44-$CaCl_2$-28	35% SL-0.44-$CaCl_2$-14	35% SL-0.44-$CaCl_2$-28	50% SL-0.44-$CaCl_2$-14	50% SL-0.44-$CaCl_2$-28	50% SL-0.44-RE-$CaCl_2$-14	50% SL-0.44-RE-$CaCl_2$-28
		0.040	0.036	0.043	0.047	0.048	0.040	0.033	0.034	0.094	0.082	0.107	0.100
Control–0.44-$CaCl_2$-14	0.040												
Control–0.44-$CaCl_2$-28	0.036	6.6E-01											
Control–0.44-RE-$CaCl_2$-14	0.043	7.6E-01	3.4E-01										
Control–0.44-RE-$CaCl_2$-28	0.047	4.7E-01	1.4E-01	5.5E-01									
20% SL-0.44-$CaCl_2$-14	0.048	4.4E-01	1.9E-01	5.2E-01	8.1E-01								
20% SL-0.44-$CaCl_2$-28	0.040	9.5E-01	4.9E-01	5.3E-01	1.4E-01	2.5E-01							
35% SL-0.44-$CaCl_2$-14	0.033	4.8E-01	7.0E-01	2.1E-01	8.0E-02	1.3E-01	2.6E-01						
35% SL-0.44-$CaCl_2$-28	0.034	6.0E-01	8.4E-01	3.8E-01	2.2E-01	2.3E-01	5.2E-01	9.4E-01					
50% SL-0.44-$CaCl_2$-14	0.094	6.8E-03	2.6E-03	4.2E-03	4.3E-03	9.6E-03	2.0E-03	2.2E-03	5.2E-03				
50% SL-0.44-$CaCl_2$-28	0.082	2.7E-02	1.3E-02	2.2E-02	2.7E-02	4.5E-02	1.3E-02	1.1E-02	1.9E-02	4.0E-01			
50% SL-0.44-RE-$CaCl_2$-14	0.107	2.6E-03	9.3E-04	1.4E-03	1.3E-03	3.2E-03	5.9E-04	8.1E-04	2.1E-03	2.7E-01	1.1E-01		
50% SL-0.44-RE-$CaCl_2$-28	0.100	1.6E-03	2.7E-04	4.0E-04	2.3E-04	1.7E-03	3.8E-05	2.3E-04	1.4E-03	4.6E-01	1.5E-01	4.3E-01	

Red shading indicates that the differences are statistically significant

Table C.2e: Student's t-test results showing statistical significance (*p*-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	Control–0.44-$CaCl_2$-14	Control–0.44-$CaCl_2$-28	Control–0.44-RE-$CaCl_2$-14	Control–0.44-RE-$CaCl_2$-28	20% FA-0.44-$CaCl_2$-14	20% FA-0.44-$CaCl_2$-28	35% FA-0.44-$CaCl_2$-14	35% FA-0.44-$CaCl_2$-28	50% FA-0.44-$CaCl_2$-14	50% FA-0.44-$CaCl_2$-28	50% FA-0.44-RE-$CaCl_2$-14	50% FA-0.44-RE-$CaCl_2$-28
		0.040	0.036	0.043	0.047	0.028	0.022	0.028	0.042	0.058	0.084	0.052	0.067
Control–0.44-$CaCl_2$-14	0.040												
Control–0.44-$CaCl_2$-28	0.036	6.6E-01											
Control–0.44-RE-$CaCl_2$-14	0.043	7.6E-01	3.4E-01										
Control–0.44-RE-$CaCl_2$-28	0.047	4.7E-01	1.4E-01	5.5E-01									
20% FA-0.44-$CaCl_2$-14	0.028	2.0E-01	1.9E-01	3.5E-02	6.3E-03								
20% FA-0.44-$CaCl_2$-28	0.022	8.1E-02	5.1E-02	1.3E-02	2.9E-03	2.3E-02							
35% FA-0.44-$CaCl_2$-14	0.028	1.8E-01	1.7E-01	3.3E-02	6.1E-03	7.2E-01	3.5E-02						
35% FA-0.44-$CaCl_2$-28	0.042	8.3E-01	4.3E-01	9.2E-01	5.3E-01	6.8E-02	2.6E-02	6.4E-02					
50% FA-0.44-$CaCl_2$-14	0.058	9.0E-02	1.6E-02	5.0E-02	6.3E-02	5.5E-04	4.0E-04	5.7E-04	6.4E-02				
50% FA-0.44-$CaCl_2$-28	0.084	1.4E-02	5.0E-03	8.7E-03	9.5E-03	1.6E-03	1.1E-03	1.6E-03	1.0E-02	2.9E-02			
50% FA-0.44-RE-$CaCl_2$-14	0.052	3.7E-01	1.8E-01	4.2E-01	6.2E-01	5.4E-02	2.8E-02	5.2E-02	4.1E-01	5.2E-01	4.4E-02		
50% FA-0.44-RE-$CaCl_2$-28	0.067	1.3E-01	7.8E-02	1.4E-01	1.8E-01	3.6E-02	2.3E-02	3.5E-02	1.4E-01	5.0E-01	3.1E-01	3.6E-01	

Red shading indicates that the differences are statistically significant

Table C.3a: Student's t-test results showing statistical significance (*p*-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	Control–0.38-NaCl-14	Control–0.38-NaCl-28	Control–0.38-$CaCl_2$-14	Control–0.38-$CaCl_2$-28	Control–0.44-NaCl-14	Control–0.44-NaCl-28	Control–0.44-$CaCl_2$-14	Control–0.44-$CaCl_2$-28	Control–0.44-RE-NaCl-14	Control–0.44-RE-NaCl-28	Control–0.44-RE-$CaCl_2$-14	Control–0.44-RE-$CaCl_2$-28
		0.013	0.012	0.022	0.016	0.018	0.019	0.040	0.036	0.017	0.022	0.043	0.047
Control–0.38-NaCl-14	0.013												
Control–0.38-NaCl-28	0.012	2.2E-01											
Control–0.38-$CaCl_2$-14	0.022	1.0E-02	7.4E-03										
Control–0.38-$CaCl_2$-28	0.016	8.6E-02	3.9E-02	5.0E-02									
Control–0.44-NaCl-14	0.018	5.7E-02	3.1E-02	1.5E-01	4.5E-01								
Control–0.44-NaCl-28	0.019	2.9E-02	1.8E-02	2.9E-01	2.1E-01	5.9E-01							
Control–0.44-$CaCl_2$-14	0.040	2.3E-02	2.0E-02	8.0E-02	3.4E-02	4.3E-02	5.2E-02						
Control–0.44-$CaCl_2$-28	0.036	8.4E-03	7.0E-03	5.1E-02	1.4E-02	2.1E-02	2.7E-02	6.6E-01					
Control–0.44-RE-NaCl-14	0.017	1.4E-02	1.0E-02	6.6E-02	4.9E-01	7.4E-01	3.3E-01	3.8E-02	1.6E-02				
Control–0.44-RE-NaCl-28	0.022	2.7E-02	1.8E-02	9.8E-01	9.6E-02	2.2E-01	3.8E-01	8.4E-02	5.9E-02	1.3E-01			
Control–0.44-RE-$CaCl_2$-14	0.043	3.0E-03	2.6E-03	1.3E-02	4.7E-03	6.5E-03	8.0E-03	7.6E-01	3.4E-01	5.0E-03	1.6E-02		
Control–0.44-RE-$CaCl_2$-28	0.047	6.3E-04	5.8E-04	3.2E-03	1.0E-03	1.5E-03	1.9E-03	4.7E-01	1.4E-01	1.0E-03	4.3E-03	5.5E-01	

Red shading indicates that the differences are statistically significant

Table C.3b: Student's t-test results showing statistical significance (*p*-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	20% SL-0.38-NaCl-14	20% SL-0.38-NaCl-28	20% SL-0.38-$CaCl_2$-14	20% SL-0.38-$CaCl_2$-28	20% FA-0.38-NaCl-14	20% FA-0.38-NaCl-28	20% FA-0.38-$CaCl_2$-14	20% FA-0.38-$CaCl_2$-28	20% SL-0.44-NaCl-14	20% SL-0.44-NaCl-28	20% SL-0.44-$CaCl_2$-14	20% SL-0.44-$CaCl_2$-28	20% FA-0.44-NaCl-14	20% FA-0.44-NaCl-28	20% FA-0.44-$CaCl_2$-14	20% FA-0.44-$CaCl_2$-28
		0.021	0.028	0.038	0.037	0.021	0.023	0.022	0.018	0.028	0.036	0.048	0.040	0.030	0.030	0.028	0.022
20% SL-0.38-NaCl-14	0.021																
20% SL-0.38-NaCl-28	0.028	3.1E-02															
20% SL-0.38-$CaCl_2$-14	0.038	7.6E-04	1.0E-02														
20% SL-0.38-$CaCl_2$-28	0.037	1.8E-04	6.8E-03	5.2E-01													
20% FA-0.38-NaCl-14	0.021	7.3E-01	1.9E-02	4.4E-04	4.3E-05												
20% FA-0.38-NaCl-28	0.023	3.7E-01	9.5E-02	1.8E-03	7.1E-04	2.2E-01											
20% FA-0.38-$CaCl_2$-14	0.022	3.5E-01	4.0E-02	5.6E-04	3.3E-05	1.0E-01	7.3E-01										
20% FA-0.38-$CaCl_2$-28	0.018	6.5E-02	6.4E-03	2.7E-04	3.0E-05	4.6E-02	3.4E-02	6.6E-03									
20% SL-0.44-NaCl-14	0.028	4.7E-02	9.2E-01	1.9E-02	1.6E-02	3.3E-02	1.2E-01	6.4E-02	1.2E-02								
20% SL-0.44-NaCl-28	0.036	8.7E-04	1.8E-02	3.4E-01	5.1E-01	4.4E-04	2.3E-03	5.6E-04	2.6E-04	3.4E-02							
20% SL-0.44-$CaCl_2$-14	0.048	1.3E-02	3.5E-02	1.9E-01	1.5E-01	1.2E-02	1.7E-02	1.5E-02	9.0E-03	3.8E-02	1.3E-01						
20% SL-0.44-$CaCl_2$-28	0.040	6.4E-04	7.0E-03	5.0E-01	1.8E-01	3.9E-04	1.4E-03	4.9E-04	2.5E-04	1.2E-02	1.4E-01	2.5E-01					
20% FA-0.44-NaCl-14	0.030	4.1E-02	5.6E-01	5.3E-02	5.8E-02	3.1E-02	8.6E-02	5.3E-02	1.3E-02	6.4E-01	1.0E-01	5.4E-02	3.3E-02				
20% FA-0.44-NaCl-28	0.030	2.5E-03	3.4E-01	7.4E-03	1.3E-03	7.4E-04	1.2E-02	1.0E-03	3.2E-04	4.9E-01	1.3E-02	4.3E-02	4.8E-03	1.0E+00			
20% FA-0.44-$CaCl_2$-14	0.028	3.9E-03	6.6E-01	4.4E-03	6.0E-04	1.0E-03	2.1E-02	1.5E-03	4.0E-04	8.1E-01	6.8E-03	3.6E-02	3.0E-03	6.9E-01	3.0E-01		
20% FA-0.44-$CaCl_2$-28	0.022	5.4E-01	8.7E-02	2.0E-03	9.6E-04	3.7E-01	8.3E-01	9.7E-01	6.1E-02	1.1E-01	2.7E-03	1.7E-02	1.6E-03	7.8E-02	1.4E-02	2.3E-02	

Red shading indicates that the differences are statistically significant

Table C.3c: Student's t-test results showing statistical significance (*p*-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	35% SL-0.44-NaCl-14	35% SL-0.44-NaCl-28	35% SL-0.44-$CaCl_2$-14	35% SL-0.44-$CaCl_2$-28	35% FA-0.44-NaCl-14	35% FA-0.44-NaCl-28	35% FA-0.44-$CaCl_2$-14	35% FA-0.44-$CaCl_2$-28
		0.062	0.074	0.033	0.034	0.047	0.051	0.028	0.042
35% SL-0.44-NaCl-14	0.062								
35% SL-0.44-NaCl-28	0.074	5.9E-02							
35% SL-0.44-$CaCl_2$-14	0.033	9.2E-03	1.7E-03						
35% SL-0.44-$CaCl_2$-28	0.034	3.5E-02	8.9E-03	9.4E-01					
35% FA-0.44-NaCl-14	0.047	7.5E-02	7.7E-03	9.9E-02	2.2E-01				
35% FA-0.44-NaCl-28	0.051	2.4E-01	3.4E-02	9.7E-02	1.8E-01	6.8E-01			
35% FA-0.44-$CaCl_2$-14	0.028	1.0E-03	9.7E-05	3.4E-01	5.0E-01	1.5E-02	2.9E-02		
35% FA-0.44-$CaCl_2$-28	0.042	4.4E-02	6.6E-03	2.8E-01	4.4E-01	5.2E-01	3.7E-01	6.4E-02	

Red shading indicates that the differences are statistically significant

Table C.3d: Student's t-test results showing statistical significance (*p*-value) of differences in cumulative scaling mass losses

Mixtures	Average cumulative mass loss at 56 cycles (lb/ft^2)	50% SL-0.44-NaCl-14	50% SL-0.44-NaCl-28	50% SL-0.44-$CaCl_2$-14	50% SL-0.44-$CaCl_2$-28	50% SL-0.44-RE-NaCl-14	50% SL-0.44-RE-NaCl-28	50% SL-0.44-RE-$CaCl_2$-14	50% SL-0.44-RE-$CaCl_2$-28	50% FA-0.44-NaCl-14	50% FA-0.44-NaCl-28	50% FA-0.44-$CaCl_2$-14	50% FA-0.44-$CaCl_2$-28	50% FA-0.44-RE-NaCl-14	50% FA-0.44-RE-NaCl-28	50% FA-0.44-RE-$CaCl_2$-14	50% FA-0.44-RE-$CaCl_2$-28
		0.196	0.179	0.094	0.082	0.187	0.156	0.107	0.100	0.147	0.266	0.058	0.084	0.154	0.205	0.052	0.067
50% SL-0.44-NaCl-14	0.196																
50% SL-0.44-NaCl-28	0.179	4.0E-01															
50% SL-0.44-$CaCl_2$-14	0.094	3.8E-04	1.0E-02														
50% SL-0.44-$CaCl_2$-28	0.082	5.5E-04	8.1E-03	4.0E-01													
50% SL-0.44-RE-NaCl-14	0.187	4.2E-01	6.9E-01	1.0E-03	1.2E-03												
50% SL-0.44-RE-NaCl-28	0.156	2.0E-03	2.5E-01	1.2E-03	1.8E-03	1.8E-02											
50% SL-0.44-RE-$CaCl_2$-14	0.107	4.8E-04	1.7E-02	2.7E-01	1.1E-01	1.5E-03	1.8E-03										
50% SL-0.44-RE-$CaCl_2$-28	0.100	9.6E-05	1.0E-02	4.6E-01	1.5E-01	5.1E-04	4.1E-05	4.3E-01									
50% FA-0.44-NaCl-14	0.147	3.6E-02	2.3E-01	3.3E-02	2.2E-02	7.5E-02	5.8E-01	6.8E-02	3.6E-02								
50% FA-0.44-NaCl-28	0.266	5.7E-02	4.8E-02	3.1E-03	2.7E-03	4.4E-02	1.3E-02	4.0E-03	3.1E-03	1.6E-02							
50% FA-0.44-$CaCl_2$-14	0.058	2.4E-05	2.2E-03	1.0E-02	7.6E-02	1.1E-04	5.9E-06	2.5E-03	3.9E-04	4.1E-03	1.3E-03						
50% FA-0.44-$CaCl_2$-28	0.084	2.5E-04	6.9E-03	3.9E-01	9.0E-01	6.8E-04	6.1E-04	8.2E-02	1.0E-01	1.9E-02	2.5E-03	2.9E-02					
50% FA-0.44-RE-NaCl-14	0.154	2.1E-02	2.8E-01	8.1E-03	6.7E-03	6.1E-02	8.8E-01	1.6E-02	6.1E-03	7.0E-01	1.6E-02	7.1E-04	4.5E-03				
50% FA-0.44-RE-NaCl-28	0.205	6.2E-01	3.3E-01	3.1E-03	2.7E-03	3.8E-01	3.6E-02	4.5E-03	2.8E-03	5.5E-02	1.1E-01	7.8E-04	2.2E-03	5.3E-02			
50% FA-0.44-RE-$CaCl_2$-14	0.052	1.4E-04	2.6E-03	2.0E-02	7.8E-02	3.2E-04	2.7E-04	7.0E-03	5.4E-03	5.1E-03	1.4E-03	5.2E-01	4.4E-02	1.4E-03	1.0E-03		
50% FA-0.44-RE-$CaCl_2$-28	0.067	7.1E-04	6.2E-03	1.4E-01	4.0E-01	1.3E-03	2.1E-03	5.0E-02	6.1E-02	1.5E-02	2.3E-03	5.0E-01	3.1E-01	5.5E-03	2.4E-03	3.6E-01	

Red shading indicates that the differences are statistically significant