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Laboratory Performance of Pervious Concrete Subjected to Deicing Salts and Freeze-Thaw

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ABSTRACT

Significant research and development have occurred for pervious concrete, but its acceptance in cold climates is still limited. Vulnerability to freeze-thaw and salt exposure has led to uncertainty about its long-term performance. Additionally, the current standardized freeze-thaw testing procedure is not recommended for pervious concrete, as it is not representative of field conditions. This study employed testing processes that are more representative of field conditions to determine the effects of the inclusion of sand as a fine aggregate; fly ash, slag and silica fume as cementitious alternatives, and construction practices on freeze-thaw durability and deicing salts exposure of pervious concrete. The use of pervious concrete itself is considered a best management practice in stormwater management; possibility of substituting cement with a waste product such as fly ash, slag and silica fume promotes sustainability even further.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Some pervious concrete installations in New England have not performed well, most likely owing to harsh winters, particularly freeze-thaw and winter maintenance activities such as application of deicing salts. Therefore, the overall scope of this research was to: (1) evaluate in the laboratory pervious concrete mixes for their resistance to deicing chemicals; (2) quantify the effects of concrete ingredients (e.g. sand, fly ash, etc.) on the resistance to freeze-thaw and deicing salts; (3) evaluate some admixtures/treatments to determine if they improve resistance of pervious concrete to deicing salts; (4) determine how curing time affects resistance to deicing salts; and (5) determine how salt guard affects resistance to deicing salts. The specific objectives of this laboratory study were to:

- quantify the mechanical and hydraulic properties of pervious concrete for various mix designs;
- examine the effects of deicing salts on pervious concrete in a freeze-thaw environment;
- quantify how the presence of sand affects compressive strength, hydraulic conductivity and freeze-thaw durability of pervious concrete;
- quantify how replacement of cement with fly ash, slag , or slag with silica fume affects compressive strength, hydraulic conductivity and freeze-thaw durability of pervious concrete;
- examine how curing time affects resistance of pervious concrete to deicing salts; and
- examine how Salt Guard affects resistance of pervious concrete to deicing salts.

1.2 ORGANIZATION OF THIS REPORT

The remainder of this report comprises three additional chapters. Chapter 2 presents a brief literature review. Chapter 3 presents the details and results of the experimental investigation performed. Recommendations for future research are presented in Chapter 4.

CHAPTER 2

BACKGROUND LITERATURE

2.1 BACKGROUND OF PERVIOUS CONCRETE PAVEMENT

Pervious concrete is a structural pavement surface, designed to allow the flow of water through its surface. It has been used in the United States since the 1970's in southern regions. Its development has been driven by interests in new and sustainable building practices, specifically because of its large infiltration capacity (Ghafoori and Dutta 1995). Pervious concrete application has been typically focused on low-traffic areas such as parking lots (Wanielista and Chopra 2007).

2.2 PERVIOUS CONCRETE PAVEMENTS

Pervious concrete (PC) is defined by ACI (2010) as a concrete mix design that consists of a uniform coarse aggregate (3/8" in size is most common), cement, water, and can include admixtures and/or supplementary cementitious materials. Pervious concrete pavements (PCP) differ from traditional concrete pavement systems due to the lack of fines and use of uniformly graded aggregate creating large interconnected voids (Ferguson, 2005). These voids typically comprise 25%-30% of the total volume of pervious concrete; allowing for connections between the top and bottom of the pavement surface. A thin coat of cement paste surrounds the aggregate providing rigidity and strength (Ghafoori and Dutta, 1995). Pervious concrete has been used in several ways including (1) concrete walls where lightweight construction is required, (2) base course for underlying city streets, (3) bridge embankments, (4) beach structures and seawalls, and (5) surface course for parking lots, low-volume roads and driveways (Ghafoori and Dutta, 1995). For the purposes of this study pervious concrete will be investigated for use as a surface course paving material.

2.3 STORMWATER CONTROL

Pervious concrete, with its ability to act as both a structural pavement and a stormwater mitigation system, provides a unique ability to efficiently manage stormwater runoff. Pervious concrete is an open graded building material, composed of fine aggregate, little to no fines, cement, water, and admixture (ACI 2010).

Pervious concrete pavements are ideal for sites with limited space, where traditional stormwater collection systems may not be viable. Pervious concrete's surface allows it to be identified as a best management practice (BMP) for stormwater pollution prevention (EPA, 2000). The purpose of pervious concrete as a stormwater management system is to allow water to flow through, and collect in its underlying holding layer, where it will either be infiltrated into the subsoil or discharged off site.

The capture of the "first flush", the first inch of rainfall, contains the most polluted stormwater (Tennis, et al., 2004). Pervious concrete is able to eliminate the potential pollutants that otherwise would have made their way to nearby streams or wetlands (Leming et. al, 2007). By capturing the rainfall at its source, it reduces the runoff potential, reducing the sediment loads, and limiting the flash flood potential (Tennis, et al. 2004). Pervious concrete has been shown to remove up to 95% total suspended solids (TSS), 65% total phosphorous (TP), 85% total nitrogen (TN), and 99% metals from stormwater runoff (Schuler, 1987). Two types of pervious concrete systems are possible - passive and active systems. Passive systems are those which collect only the water that falls directly on their surface, and are designed to only remove that volume of water from the stormwater runoff system. Active systems are such that they collect not only the water that falls on them, but also that is transported from nearby impervious surfaces.

Pervious concrete has several additional advantages over conventional pavements. The infiltration of water through its interconnected pores can reduce hydroplaning potential, improve skid resistance, and reduce runoff potential (Tennis, et al., 2004). Pervious concrete has also been shown to reduce the heat island effect, storing less heat than traditional pavement surfaces (PCA 2003).

2.4 MIX DESIGN

Pervious concrete is typically described as a zero-slump, open graded material consisting of portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water (ACI, 2010). The absence or small amount of fine aggregate leads to open voids between cement-covered aggregate. Uniformly graded aggregate is typically used to maximize the void space, to create hydraulically connected paths for water to flow. Typical admixtures include high range water reducer (HRWR), air entraining admixture (AEA), viscosity modifier (VMA), and hydration control (STAB) (ACI 2010). An air entraining admixture is used to create small channels to relieve pressures during freeze-thaw cycles. High range water reducer, viscosity modifiers, and hydration control are used to achieve proper workability, delay initial curing time, and ensure proper hydration during curing.

2.4.1 Admixtures

Aside from coarse aggregate, cement and water, pervious concrete can also incorporate high-range water reducers, air entraining agents, viscosity modifying admixtures, fly ash and silica fume (ACI, 2010). High range water reducers are added to decrease the water demand of the concrete, resulting in higher compressive strength values. Air entraining admixtures are added to improve freeze-thaw resistance of traditional concrete and have been adapted for use in pervious concrete. The low workability of pervious concrete can be improved by adding viscosity-modifying admixtures to increase the flow of the cement paste surrounding the aggregate resulting in better compaction.

2.4.2 Fine Aggregate - Sand

The inclusion of fine aggregate in a mix would be adding or replacing sand or fibers to increase paste thickness, and possibly the tensile strength of the cement paste which can potentially create a more durable pervious concrete (Anderson and Dewoolkar, 2012). The benefits of increased strength and durability come from greater exposed surface area for the cement paste to bond. The inclusion of sand lowers the permeability and void ratio of the pervious concrete compared to a mix with only coarse aggregates (Schaefer et al., 2006). Sand Addition showed increased freeze-thaw resistance in some studies (Schaefer et al., 2006). Experiments have incorporated up to 15% fine sand, as a mass ratio of fine aggregate to coarse aggregate, while 5% to 10% was found to be an optimal amount to improve strength (Schaefer et al., 2006). It has been suggested that sand is added to the aggregate instead of replacing the mass to keep the ratios of aggregate to cement consistent (Schaefer et al., 2006).

2.4.3 Fly Ash

Fly ash is a byproduct of the combustion of coal used for generation of electricity. Of the fly ash generated through coal energy combustion, 20% has been used annually in concrete production (Helmuth 1987). As a byproduct material, there is no associated carbon dioxide produced to make fly ash, and unused fly ash would be discarded into landfills as unrecyclable waste. Cement production by comparison is responsible for 5% of global carbon dioxide production (Worrell et al. 2001). From a health stand point by recycling fly ash it is preventing the disposal of fly ash into potential groundwater where it has been found to contaminate wells near disposal locations (MDE 2007). Fly ash is a small spherical particle, typically 0.2-10 μm, which occurs when mineral impurities fuse during combustion (Chindaprasirt et al., 2005). By comparison, the particle size of type I-II cement on average is between 10-20 μm (Bentz et al., 2008). Fly ash is categorized based on ASTM 618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete,* with most concretes incorporating class C or F fly ash (ASTM, 2014). Fly ash is the most commonly added supplementary cementitious material, with about 50% of all ready-mix concrete incorporating some amount of fly ash (PCA, 2002). Fly ash addition in conventional concrete has been shown to reduce water demand, similar to chemical water reducing admixtures (Helmuth, 1987). The small spherical particles act to lubricate the cement, improving workability, and can extend the set time (Chindaprasirt et al., 2004). Fly ash has been shown to increase the long-term compressive strength of conventional concrete, but requires curing beyond the typical 28 days (Chindaprasirt et al., 2004; PCA, 2002). The smaller particle size relative to cement allows for a greater distribution of particle sizes, which can act to reduce the pore sizes of the cement paste (Chindaprasirt et al., 2005). Finer fly ash, those with smaller particles were shown to further reduce porosity, pore size, and improve strength and workability (Chindaprasirt et al., 2004; Chindaprasirt et al., 2005). While fly ash has been used in conventional concrete for some time, it is still being investigated in pervious concrete. Anderson and Dewoolkar (2012) showed improved freeze-thaw durability with the inclusion of 10-20 % fly ash.

2.4.4 Slag

Slag is a byproduct of the production of steel. The slag forms when the silica and alumina compounds of the iron ore combine with the calcium of the fluxing stone (limestone and dolomite). The newly formed slag floats on the liquid iron and is drawn off from a notch at the top of the hearth while the liquid iron flows from a hole at the bottom of the hearth. These reactions take place at temperatures ranging from 1300-1600^{o}C, so the slag is conveyed to a pit where it is cooled. The United States produces approximately 14 million metric tons of blast furnace slag annually (NSA, 1988). The conditions of the cooling process determine the type of blast furnace slag: air-cooled, foamed, water granulated, or pelletized. Of these types, ground granulated blast furnace slag is both cementitious and pozzolanic. Ground granulated blast furnace slag is a replacement of portland cement and provides several advantages such as improved workability, reduced heat of hydration, decreased costs increased resistance to alkali-silica reaction, and sulfate resistance and increased compressive and flexural strength when compared to unblended portland cement.

2.4.5 Silica Fume

Silica fume is a by-product of the smelting process in the silicon metal and ferrosilicon industry. Silica fume is produced when SiO vapors, produced from the reduction of quartz to silicon, are condensed. In the United States, approximately 100 thousand tons of silica fume is generated annually (Mehta, 1989). Silica fume particles are spherical with an average diameter of 1-μm and contain approximately 90% silicon dioxide with traces of iron, magnesium, and alkali oxides. When compared to portland cement, fly ash, or ground granulated blast furnace slag, silica fume is much finer. The addition of small amounts of silica fume (2-5%) in cement increases workability. Large amount of silica fume (>7%) in concrete decreases workability, increase compressive strength, decrease permeability and provide resistance to sulfate attack and alkali-silica reaction.

2.5 ENGINEERING PROPERTIES OF PERVIOUS CONCRETE

2.5.1 Void Ratio

Void ratio is a measure of the total open space within the pervious concrete. It is a comparison of the volume of voids, to the total volume of cement paste and aggregate. Typical void ratio for pervious concrete is 18-35% (ACI, 2010; Tennis et al., 2004). This range is considered ideal to provide enough strength, while allowing for sufficient hydraulic conductivity. Void ratio was shown to increase with a decrease in aggregate to cement ratio (Park and Tia, 2004). As the amount of cement covering each aggregate increases, the voids in pervious concrete are filled, reducing void ratio. It has been shown that void ratio increases as the unit weight decreases (Wang et al., 2006). With an overall denser sample, and a consistent density of aggregates and cement, the result is a lower void ratio.

2.5.2 Compressive Strength

Compressive strength is a typical measure of the strength of pervious concrete. Compressive strength of pervious concrete ranges from 2.8 to 28 MPa (400 to 4,000 psi) (ACI, 2010). The recommended value for compressive strength for general use is 2,500 psi (~17 MPa), and at this strength the pervious concrete should meet all same requirements as conventional concrete pavements (Tennis et al., 2004). Compressive strength has been shown to increase with unit weight (McCain and Dewoolkar, 2010). Additionally, other properties that make for a more robust, denser, and heavier sample have shown to increase compressive strength as well. These include increasing water to cement ratio, decreasing aggregate to cement ratio, stronger coarse aggregate, greater compaction energy, and decreased void ratio (Ghafoori and Dutta, 1995; Meininger, 1988; Park and Tia, 2004; Tennis et al., 2004). Curing time also relates directly to strength, with greater strength developing with longer curing times (Ghafoori and Dutta, 1995).

2.5.3 Hydraulic Conductivity

As the key design characteristic in pervious concrete, hydraulic conductivity typically ranges from 0.2 to 1.2 cm/s (280 to 1,680 in/hr) (ACI, 1992). Such high infiltration makes pervious concrete for excellent stormwater collection. Hydraulic conductivity is directly related to the size and amount of voids present in pervious concrete. Hydraulic conductivity increases with increasing void ratio, decreasing water to cement ratio, decreasing compaction, increasing aggregate to cement ratio, decreasing unit weight, and decreasing fine aggregate (Ghafoori and Dutta, 1995; McCain and Dewoolkar, 2010; Park and Tia, 2004; Tennis et al., 2004; Wanielista and Chopra, 2007). A major concern in pervious concrete is its potential to clog, losing its infiltration capacity (McCain et al., 2010).

2.6 DURABILITY IN COLD CLIMATES

2.6.1 Freeze-Thaw

Due to the open pore structure and thin cement paste there are concerns about the ability of pervious concrete to resist cold weather climates due to freeze-thaw cycles and the application of deicing salts. Traditional concrete pavements resist freeze-thaw cycles by entraining air within the concrete. Air entraining admixtures added during construction create 4% to 8% air content in conventional concrete in the form of independent microscopic pores. These pores provide space for water to expand during freezing cycles; this reduces the overall hydraulic forces on the concrete preventing fracture. Pervious concrete has a much larger void system; typically 15-30% is needed to achieve the required infiltration capacity. Under normal conditions water passes through these voids into an underlying layer to be infiltrated or collected for discharge. If this pore space is saturated when freezing occurs, then the expanding water will stress the cement paste that bonds aggregate, leading to aggregate becoming dislodged. Although saturation such as this is not common in the field the National Ready Mixed Concrete Association (NRMCA, 2004) cites conditions that can lead to complete saturation of PCP. Complete saturation can occur in the field when pores become clogged with sand or debris preventing water from draining, or when high groundwater tables result in moisture flow into the PCP (NRMCA, 2004). Saturated freezing can be prevented by several methods; (1) properly constructing the pervious concrete lot to have a large gravel subbase that extends beyond the frost line of the soil, (2) including a drain in the gravel subbase, to ensure it remains unsaturated and (3) regular cleaning of the pervious concrete to prevent the accumulation of clogging fines.

2.6.2 Test Method

The large void spaces and thin cement paste leave pervious concrete susceptible to freeze-thaw type damage, an issue that has limited its use in cold regions. The presence of water, by design, puts pervious concrete in a vulnerable state. When fully saturated in water and frozen, the water expands forcing the aggregates apart. The standard test for freeze-thaw durability, ASTM C666 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*, consists of cycling fully saturated concrete specimens 7 times a day, until 300 cycles (ASTM, 2014). Mass loss of the samples is then measured, with 15% loss considered as failure (Schaefer et al., 2006). Tests have shown that with the addition of sand, pervious concrete can withstand over 300 freeze-thaw cycles, passing the ASTM C666 standardized test for durability (Kevern et al., 2008b). Other investigations have studied adding admixtures and fibers or changing the water to cement ratio , coarse aggregate, and moisture conditions (Ghafoori and Dutta, 1995; Kevern et al., 2008a; Schaefer et al., 2006; Wang et al., 2006; Yang et al., 2006; Yang, 2011).

The American Concrete Institute committee 522 report does not recommend the ASTM C666 test, because the test does not represent field conditions well (ACI, 2010). The fully saturated test condition and the rapid cycling of freeze-thaw make for an unrepresentative testing environment. As an alternative, testing under drained condition and one freeze-thaw cycle per day has been recommended by some researchers (Olek and Weiss, 2003; Yang, 2011). It has been suggested that increased saturation conditions are needed for damage and that below the critical saturation levels, no damage would occur in pervious concrete from freezing and thawing (Yang et al., 2006). Critical saturation in conventional concrete is expected to be about 60% for the freeze-thaw damage to occur (Litvan, 1973; Vuorinnen, 1970). Additionally, frozen water in the large pores of pervious concrete acts to create negative vapor pressures, drawing the liquid water through the cement paste, causing scaling damage (Harnik et al., 1980).

2.6.3 Damage

Damage to PCP during freeze-thaw cycles is typically one of the following: internal paste deterioration, surface scaling, and D-cracking (ACI, 1992). Surface scaling, the loss of paste or mortar from the surface of the concrete, is the most common damage, and typically removes layers less than 1 mm (ACI, 1992). D-cracking, which is characterized as internal failure in a nondurable aggregate generally occurs near the edges and joints, and is a result of expansion in the aggregate (Sawan, 1987). Internal paste deterioration typically occurs from the internal pressure in the pore structure that generates when freezing occurs during critical saturation (Pigeon, 1994).

2.6.4 Durability

The type of materials, their properties, and the ratios at which they are included in the construction of pervious concrete can have significant effects on the freeze-thaw durability as well. Kevern, et al. (2010) suggest that the key factor for freeze-thaw durability is the aggregate absorption, and recommend absorption of less than 2.5% by sample mass for high durability mixes. The addition of sand has been shown to improve freeze-thaw durability in rapid freeze-thaw testing (Schaefer et al., 2006). Increased water to cement ratio has been shown to improve freeze-thaw durability in slow freeze-thaw testing in water cured samples (Yang, 2011). The use of air entraining admixtures has been shown to both improve freeze-thaw durability in rapid cycles (Kevern et al., 2008a; Yang et al., 2006) and have no effect in slow cycles (Yang, 2011). Kevern, et al. (2008b) reported that by adding fibers freeze-thaw durability and workability can be improved without sacrificing infiltration potential.

2.6.5 Effects of Deicing Salts

In cold climates, road salts are used to melt snow and ice on pavements. The commonly used salts are sodium chloride and calcium chloride. Salt exposure in concrete can lead salt crystals to form in the pores, and at high concentrations can change the chemical composition in the cement paste (Darwin et al., 2007). The chemical reaction causes the cement paste to lose its structure, and the bonds can be destroyed (Cody, et al., 1996; Lee, et al., 2000).

Studies have shown that a 2-4% percent solution of salt causes maximum scaling (cement paste to be dislodged) in saturated conditions, and that above and below this range less scaling is expected (Verbek and Kleiger, 1957, Marchand et al., 1999). Conversely, for the wetting-drying condition, the amount of damage increases as the concentration of salt increases (Cody et al., 1996). Freeze-thaw testing conducted with a 3% sodium chloride solution also showed that as the solution freezes, the concentration of the unfrozen solution can rise to nearly 4 times the original concentration (Chan, 2007). The effect, known as freeze concentration, is believed to aid in the process of supercooling. Supercooling occurs when the freezing point of the solution is depressed because of the salt concentrations, until the point where the phase shift in the water occurs, and at much larger pore pressures (Harnik, et al., 1980).

Harnik, et al. (1980) state that the application of deicing salts allows the degree of saturation in conventional concrete to exceed the amount normally attainable with pure water. Additionally salt crystallization is identified as a source of pressure in the large pores in concrete, by both physical forces, and hydraulic pressures as it draws water out of the smaller pores.

Pigeon and Pleau (1995) have shown that in the ASTM C666 rapid freeze-thaw testing the use of air entraining admixtures can significantly improve the deicing scaling resistance. Yang (2011) however showed that in a slower, one cycle per day testing, no increase in durability was seen; and suggests it may be due to the additional air voids becoming saturated in the longer freeze-thaw cycles. Anderson and Dewoolkar (2012) showed that in a one cycle per day freeze-thaw testing, salt application at 8% produced the greatest damage.

2.6.6 Salt Guard

Salt Guard is a general-purpose silane/siloxane water repellent and chloride screen often used on conventional concrete and masonry. It minimizes chloride ion penetration from deicing chemicals, acid precipitation, salt air, and water in marine environments and thus reduces corrosion of the reinforcing steel from chloride exposure. Salt Guard is commonly used to reduce spalling of new conventional concrete surfaces due to freeze-thaw cycling. The chemicals reacts with concrete and masonry components for long lasting protection. The compound penetrates deeply for maximum protection, and seals pores and capillaries of substrate preventing liquid absorption while allowing excellent vapor transmission. Salt guard exceeds National VOC Emission Standards for Architectural Coatings 40 CFR Part 59 (< 600 g/L). Salt guard is generally applied with a low pressure, airless sprayer.

CHAPTER 3

EXPERIMENTAL PROGRAM AND RESULTS

3.1 OVERALL EXPERIMENTAL PROGRAM

The experimental program included two components. Some experiments were conducted at the University of Vermont (UVM), and others were conducted at Norwich University (Norwich). This section described the details of experimental programs and analysis of experimental results.

3.2 EXPERIMENTAL DETAILS

The specific objective of this study was to investigate the resistance of pervious concrete to freeze-thaw and salt exposure. The pervious concrete mix design included varying amounts of sand, and cementitious alternative, including fly ash, slag, and silica fume. Two methods of compaction were used in experimentation; hand dropping and a vibration table. Lastly the application of salt guard, either dipped or sprayed was tested. Pervious concrete specimens were prepared and tested to mimic field conditions, including moist air curing, once daily freeze-thaw cycles, and allowing for the specimens to be fully drained. By varying the contents of the mix, the compaction method, application of salt guard, and the concentration of salt in solution, the damage and durability of the pervious concrete was studied.

3.2.1 Mix Designs and Specimen Preparation

The focus of these tests were to observe a wide range of variables that could potentially affect the performance of pervious concrete in a controlled freeze-thaw environment. These options are displayed in Table 3.1. The pervious concrete mix designs used in this study are summarized in Tables 3.2. Pervious concrete specimens were prepared in general accordance with ASTM C192, *Practice for Making and Curing Concrete Test Specimens in the Laboratory* (ASTM, 2014). Though other preparation methods have been used elsewhere, ASTM C192 remains the standard for preparing laboratory samples. Specimens were cast into cylinders with diameter 4” (10.2 cm) and length 6” (20.3 cm). The drop method of compaction was tested at the UVM labs while the vibration method was tested at Norwich. The drop compaction method procedure is to fill the 6-inch diameter mold up half way with the wet concrete then lift the mold by about 1 inch (~2.5 cm) from a solid foundation and drop it. This is repeated 10 times. Then the remaining space in the mold is filled with wet concrete and the mold is dropped 10 more times. The specimen is finished by striking off the excess material from the top and capping the mold for the first 7 days of moist curing. The vibration method of compaction conducted at Norwich University is to fill the mold with wet concrete to the top and placing it on a vibrating table until the wet concrete does not compact any further. The excess is then scraped off and the mold is capped.

Table 3.1- Experimental variables

Mix Variables				
Compaction Method	Cement Content	% Sand	Curing time	Salt Guard
Drop (D)	**Cement (Base)**	**0% Sand (0%)**	**7 Days (7d)**	**None**
Vibration (V)	Cement + Slag (Slag)	5% Sand Addition (5%A)	28 Days (28d)	Dipped (D)
	Cement + Fly ash (FA)	10% Sand Addition (10%A)	54 Days (54d)	Sprayed (S)
	Cement + Slag + Silica Fume (SlagSF)	5% Sand Replacement (5%R)		
		10% Sand Replacement (10%R)		

All mix designs used the same 10 mm (3/8”) crushed ledge as its coarse aggregate. Type I-II portland cement was used for all mixtures. Chemical admixtures used included an air entraining agent (AEA), high range water reducer (HRWR), viscosity modifying admixture (VMA), and hydration controlling admixture (HCA). Class F fly ash (FA), Slag and Silica Fume were used as an additional alternative cementitious material. Details of mixes studied are summarized in Table 3.2. The labeling system noticed on the far left column of Table 3.2 and throughout the tables and graphs displayed in this report looks complex at first. The first letter represents the compaction method; either D for drop, conducted at UVM or V for vibration, conducted at Norwich. After the first underscore is the type of cement that was used in the particular mix. Base is only type II cement; Slag is type II cement with 20% replacement by slag; FA is type II cement with 20% replacement by fly ash; and SlagSF is type II cement with 20% replacement by slag and 4% replacement by silica fume. The next section describes the sand content of the particular mix. The abbreviation 5%A is 5% sand addition by percent of the mass of total aggregate, 10%A is 10% sand addition by percent of the by mass of total aggregate, 5%R is 5% sand replacement by percent mass of total aggregate, and 10%R is 10% sand replacement by percent mass of total aggregate.

Table 3.2 - Pervious concrete mix designs used in this study

Mix Design	Compaction Type	Water lbs/yd^3 (kg/m3)	Aggregate lbs/yd^3 (kg/m3)	Sand lbs/yd3 (kg/m3)	Cement (II) lbs/yd^3 (kg/m3)	Fly Ash lbs/yd^3 (kg/m3)	Slag lbs/yd^3 (kg/m3)	Silica Fume lbs/yd^3 (kg/m3)	Admixtures oz/yd^3
D_Base_0%	Drop	167 (99.01)	2792 (1656.21)	-	610 (362)	-	-	-	
D_Base_5%R	Drop	167 (99)	2642 (1567)	150 (89)	610 (362)	-	-	-	AEA: 2
D_Base_5%A	Drop	167 (99)	2792 (1656)	150 (89)	610 (362)	-	-	-	
D_Base_10%R	Drop	167 (99)	2492 (1478)	300 (178)	610 (362)	-	-	-	HRWR: 18.6
D_Base_10%A	Drop	167 (99)	2792 (1656)	300 (178)	610 (362)	-	-	-	
D_FA_5%A	Drop	167 (99)	2792 (1656)	150 (89)	490 (291)	120 (71)	-	-	VMA: 61
D_Slag_5%A	Drop	167 (99)	2792 (1656)	150 (89)	490 (291)	-	120 (71)	-	
D_SlagSF_5%A	Drop	167 (99)	2792 (1656)	150 (89)	464 (275)	-	116 (69)	31 (18)	STAB: 61
D_SlagSF_10%A	Drop	167 (99)	2792 (1656)	300 (178)	464 (275)	-	116 (69)	31 (18)	
V_Slag_5%A	Vibration	167 (99)	2792 (1656)	150 (89)	490 (291)	-	120 (71)	-	
V_Slag_10%A	Vibration	167 (99)	2792 (1656)	300 (178)	490 (291)	-	120 (71)	-	

Specimens were moist cured at 23 ± 2°C (73.4 ±7.2°F) for 7, 28 (the standard) or 54 days but were demolded after the initial 7 days, to better replicate field conditions. The labeling system for curing time is either 7d for 7 days curing, 28d for 28 days curing, or 54d for 54 days curing. The control for each of these variables is shown in bold in Table 3.1. The specimens were used for testing in slow freeze-thaw chambers, to better replicate field conditions, rather than the typical ASTM C666 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing* (ASTM, 2014). Conventional performance properties of compressive strength, hydraulic conductivity, and void content were also measured.

The effects of varying sand content, varying cement replacement, varying curing time for cement replacement, and compaction method are recorded and analyzed.

3.2.2 Void Ratio

The void ratio was determined in accordance with ASTM C1754 by taking the difference in weights of an oven dried specimen, and when submerged in water, using Equation 1. (ASTM, 2014) Void ratio testing took place on three specimens from each mix design, with each specimen tested three times.

$$V_r = \left[1 - \left(\frac{M_w - M_d}{\rho_w \times Vol}\right)\right] \tag{1}$$

where,

V_r = void ratio,

M_w = mass in water (M),

M_d = dry specimen mass (M),

ρ_w= density of water (M/L^3),

Vol = volume of specimen (L^3).

3.2.3 Compressive Strength

Compressive strength was determined in general accordance with ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. (ASTM, 2014). The specimens used elastomeric pad caps in accordance with ASTM C1231, *Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders*. (ASTM, 2014). Compressive strength testing was done after the full 28 day curing time, and was conducted on five replicate specimens.

3.2.4 Hydraulic Conductivity

Hydraulic conductivity was determined using a falling head permeameter developed by McCain and Dewoolkar (2010). Specimens were enclosed in a mold that was coated with a flexible rubber layer. This mold was secured with hose clamps to prevent water from flowing along the edge of the sample. Water was added to the downstream end of the device to expel any air voids that may have been present in the sample. Once all voids had been filled the water level was increased to 15” (38.1 cm) above the zero head value and allowed to fall to a height of 3” (7.6 cm), the time for this to occur was recorded. Previous research has shown that for these head values, laminar flow is maintained, allowing the application of Darcy’s Law to interpret the test results (Montes and Haselbach, 2006). The hydraulic conductivity can be found using the following equation:

$$k = \frac{a \times L}{A \times t} \ln\left(\frac{h_1}{h_2}\right) \quad (2)$$

where,

k = hydraulic conductivity (L/T),

a = cross-sectional area of the standpipe (L^2),

L = length of the specimen (L),

A = cross-sectional area of the specimen (L^2),

t = time for water to drop from h_1 to h_2 (T),

h_1 = initial water level (L),

h_2 = finial water level (L).

3.2.5 Freeze-Thaw Testing – UVM

Freeze-thaw testing began after the specimens (sample size of 5) completed their respective curing time, 11 of the 15 sets tested were cured for 28 days. To better simulate field conditions, a single day freeze-thaw cycle for up to 100 days was used for this testing. The freeze-thaw cycle included 16 hours at -20°C (-4°F), and 8 hours at 25°C (77°F). The testing also included a wetting-drying phase, where the specimens were submerged in solution for the last hour of the thawing segment, then removed to drain. The specimens were allowed to freely drain until all excess solution is removed, and tipped to ensure no solution remains trapped inside. The total draining time was about 5 minutes. The specimens were placed onto open grates in the freezer, with a fan to circulate the cold air. The drained specimens are believed to be more representative of a functioning pervious concrete system. Solutions used included water and sodium chloride solution at 8% by weight, this percent was found to be the most destructive in previous pervious concrete freeze-thaw study conducted by Anderson and Dewoolkar (2012). Solutions were prepared every 10 days to ensure desired concentrations. Testing was conducted with five replicate specimens for each mix design and salt combination. Specimens were measured for mass lost every 10 days for samples in 0% salt water and every 5 days for 8% salt solutions, with testing continuing until 100 days. Mass loss of 15% was considered failure for this test as recommended by Schaefer, et al. (2006).

3.2.6 Freeze-Thaw Testing – Norwich

Freeze-thaw testing at Norwich University was conducted using a similar procedure as described above for the tests conducted at UVM. The purpose of the Norwich experiments was to examine the effects of salt guard application on pervious concrete. The specimens were either dipped in a salt guard solution or salt guard solution was sprayed on the surface of the specimens. for Norwich freeze-thaw testing. The samples had 20% slag replacement, compacted using a vibration table, and either 5% sand addition of 10% sand addition. The specimens that were dipped, are indicated in Figure 3.7 with a “D”, and those which were sprayed are labeled with an “S”.

3.3 EXPERIMENTAL RESULTS AND DISCUSSION

The void ratio, hydraulic conductivity, compressive strength, and freeze-thaw durability measurements are presented and discussed in this section. Whenever possible, comparisons to similar measurements reported in the literature are also made.

3.3.1 Engineering Properties

The typical properties that characterize pervious concrete performance are void content, hydraulic conductivity, and compressive strength. The combination of these measures provides a snapshot of the performance of the mix design. It is common to see relationships between these properties, where a mix with high void ratio will generally have high hydraulic conductivity, and low compressive strength. Table 3.3 summarizes the average results from these tests.

Void ratio, which is typically between 18-35%, was consistently high across the mix designs, averaging 30.9% (ACI, 2010; Tennis et al., 2004). Void ratio can be affected by the aggregate to cement (a/c) ratio and compaction energy. The void ratio of samples compacted from vibration was considerably greater than those that were compacted from the drop method. The average density of samples compacted from drop method is 8.17 pcf greater than the average density of samples compacted from vibration. Within the specimens that were compacted from dropping, there was no noticeable variation between the different mix designs.

Table 3.3 - Summary of average engineering properties

Mix Name	Curing (Days)	Density (pcf)	Void Ratio (%)	Hydraulic Conductivity (in/hr)	Compressive Strength (psi)
D_Base_0%	28	119.03	30.6	3,699	1,484
D_Base_5%R	28	116.58	30.8	3,940	1,524
D_Base_5%A	28	117.71	30.8	3,345	1,131
D_Base_10%R	28	118.02	29.6	3,501	1,469
D_Base_10%A	28	121.22	28.6	4,209	1,797
D_FA_5%A	7	117.46	29.3	3,359	1,279
D_FA_5%A	28	114.19	31.8	3,359	1,086
D_FA_5%A	54	115.81	30.8	3,827	1,852
D_Slag_5%A	7	119.53	30.1	3,728	1,668
D_Slag_5%A	28	119.77	29.4	3,898	1,698
D_Slag_5%A	54	121.68	28.0	3,813	1,717
D_SlagSF_5%A	28	118.97	29.6	3,359	1,529
D_SlagSF_10%A	28	116.66	30.8	3,501	1,292
V_Slag_5%A	28	107.89	38.3	5,003	862
V_Slag_10%A	28	112.18	34.8	3,997	1,168

Typically, lower density specimens show an increase in hydraulic conductivity (McCain and Dewoolkar, 2010). The hydraulic conductivity measurements showed the mixes to be above the typical range of 283 – 1,700 in/hr (NRMCA, 2004). The average hydraulic conductivity for all specimens was 3,826 in/hr with the lowest at 1,842 in/hr. These high numbers coincide with having high void ratio. The specimens prepared using vibration compaction had very high hydraulic conductivity relative to the specimens prepared using drop compaction. Mixes with slag tended to be denser while having greater hydraulic conductivity than its counterparts with fly ash and the base cement mix as can be seen in Figure 3.1. Nonetheless, all samples show high infiltration potential, above typical ranges, and show the mixes to be above the practical range for field applications.

The measured compressive strength was within the 500 - 4,000 psi.. The average compressive strength of drop compaction specimens tested was about 1, 500 psi, but falls below the recommended value of 2,500 psi (Tennis et al., 2004; NRMCA, 2004). The lowest values came from the mix of fly ash, 5% sand addition, 28 day curing, registering in at 1,087 psi. Results of the effects of cementitious alternatives on the compressive strength testing can be seen in Figure 3.2. The average for vibration compaction mixes was 1,015 psi, which is expected given their lower density. The compressive strengths did increase slightly with density increase as is typical of pervious concrete (McCain and Dewoolkar, 2010). Failure during testing did not appear to be solely through the cement paste, indicating it was not exclusively a weakness in the paste that resulted in lower than expected values.

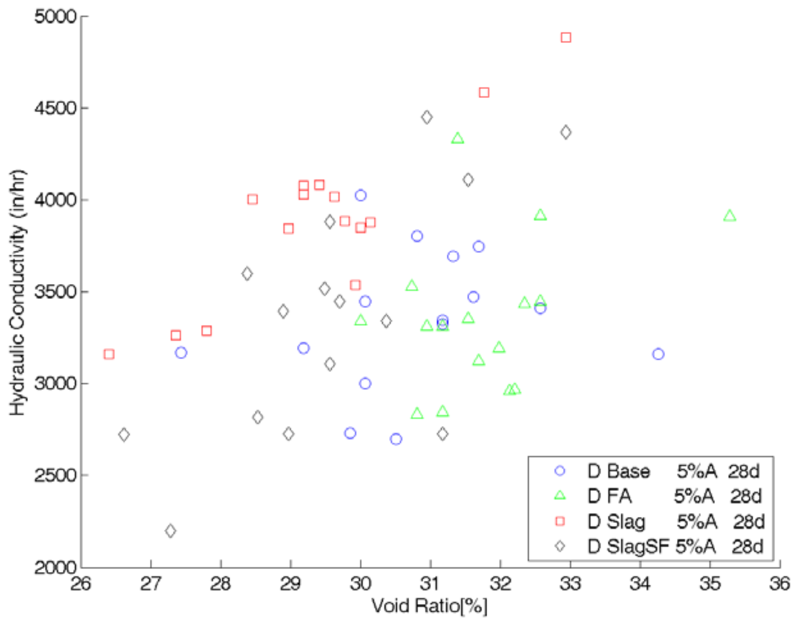

Figure 3.1 - Hydraulic Conductivity - Effects of Cement Replacement @ 5% Sand Addition

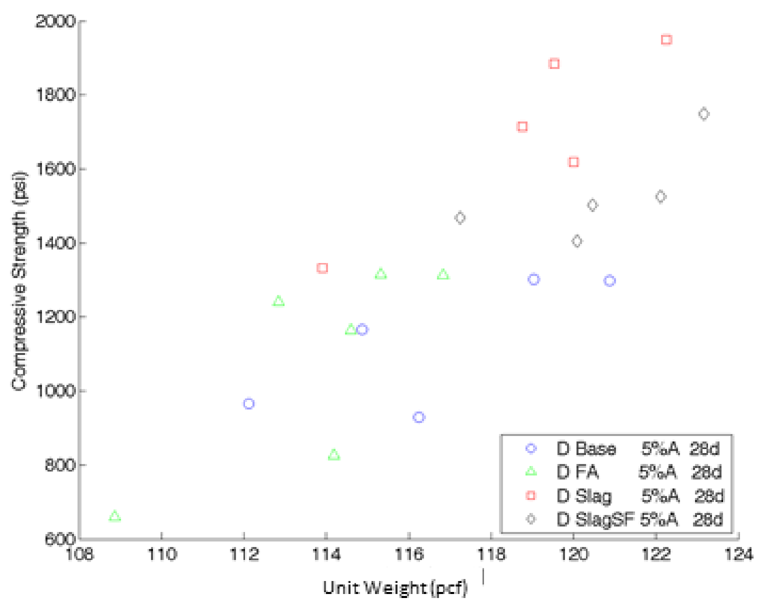

Figure 3.2 - Compressive Strength - Effects of Cement Replacement @ 5% Sand Addition

Overall, all mix designs fell within acceptable ranges for void ratio, hydraulic conductivity, and compressive strength. The results indicate that the mixes are on the high side for void ratio and hydraulic conductivity, and subsequently the lower end of compressive strength. A lower a/c ratio may provide an increase in strength, while maintaining acceptable void ratio and hydraulic conductivity. The inclusion of sand addition and replacement did not have a noticeable effect on these properties. No clear trends emerged based on the mix design alterations, suggesting that the construction and compaction play a key role in the hydraulic conductivity or compressive strength.

3.3.2 Freeze-Thaw Durability

Freeze-thaw tests were conducted to compare durability of the studied mix designs, to determine which alterations to the base mix could improve the freeze-thaw durability. Additionally, the effects of salt guard are tested. Salt concentration of 0% (water) and 8% of sodium chloride salt solution were used for specimen saturation in wetting-drying during testing. Curing time for the cementitious alternatives was tested for its effect on durability. Test including the application of salt guard also used an additional 4% salt concentration. Testing in both locations was done using a slow, one cycle per day process, in an attempt to more closely approximate field conditions. The specimens were kept submerged in solution for the last hour of the thaw, and then be allowed to drain while freezing, as is expected in the field. Failure was considered when a specimen lost 15% mass. The specimens were subjected to a maximum of 100 freeze-thaw cycles. The discussion of the freeze-thaw experiments is divided into two parts: 1) How varying mix designs and curing time of cement replacements affects pervious concretes' resistance to freeze-thaw with and without deicing salts; 2) How the proper application of salt guard to pervious concrete affects resistance to freeze-thaw damages with varying amounts of deicing salts.

All specimens survived the 0% salt concentration (water) 100-day cycle without losing more than 2% weight, as can be seen in Figure 3.3. For the specimens tested in 8% salt solution, considerable damage was seen in certain specimens (Figures 3.4 through 3.6). Each data point represents 5 specimens averaged together, with the exception of the mixes that are base cement, sand addition (5% and 10%). These tests are not averaged, as these individual specimens did not progress on a similar path as their counterparts did. Out of these ten specimens, half of them failed along a flat horizontal plane through the middle of the specimens. This type of failure could be a result of inadequate bonding in the dropping method compaction. The method uses two lifts to complete the sample construction, and the failure maybe occurring at the joint between these lifts. This inconsistency is therefore probably due to inconsistence construction when mixing or compacting laboratory specimens in small molds. Gaines in weight, seen as negative weight loss values are likely due to weighing the samples while they remained partially saturated. The initial weigh in was likely taken with a dry sample, and thus upon saturation the incremental weight increase.

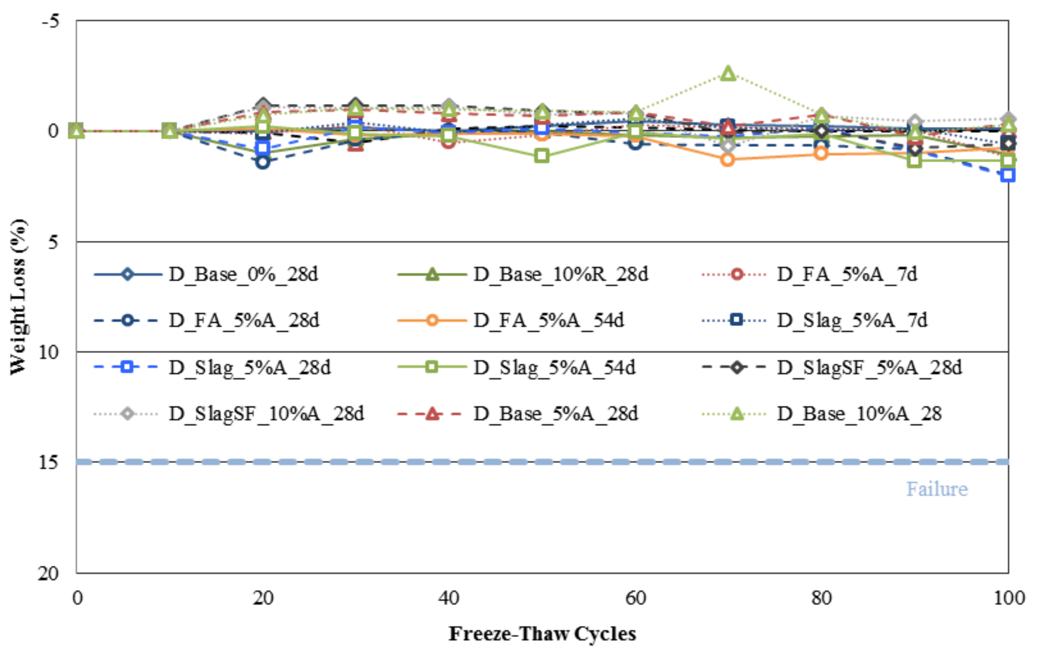

Figure 3.3 - UVM 0% Salt Solution. - All Mixes

To closely observe the results of these specimens they are plotted in three separate graphs in Figures 3.4, 3.5 and 3.6. The first graph (Figure 3.4), for 8% salt solution shows the effects of sand and its durability to freeze-thaw. The base sample with no sand has the shortest life span, lasting 25 cycles. Sand replacement of 10% was the only specimen in the particular study of sand to survive the 100 cycles. This had the highest sand to coarse aggregate ratio, showing that more sand aids in resistance to freeze-thaw damages.

The effects of cement replacements are shown in Figure 3.5, the control mix design is 28 day curing. Cement replacement of slag and silica fume (with 5% sand addition) proved to be more durable while fly ash failed after 15 cycles and again the base 5% sand addition samples did not perform consistently. Slag and Silica Fume improved freeze-thaw durability, when used in addition to sand.

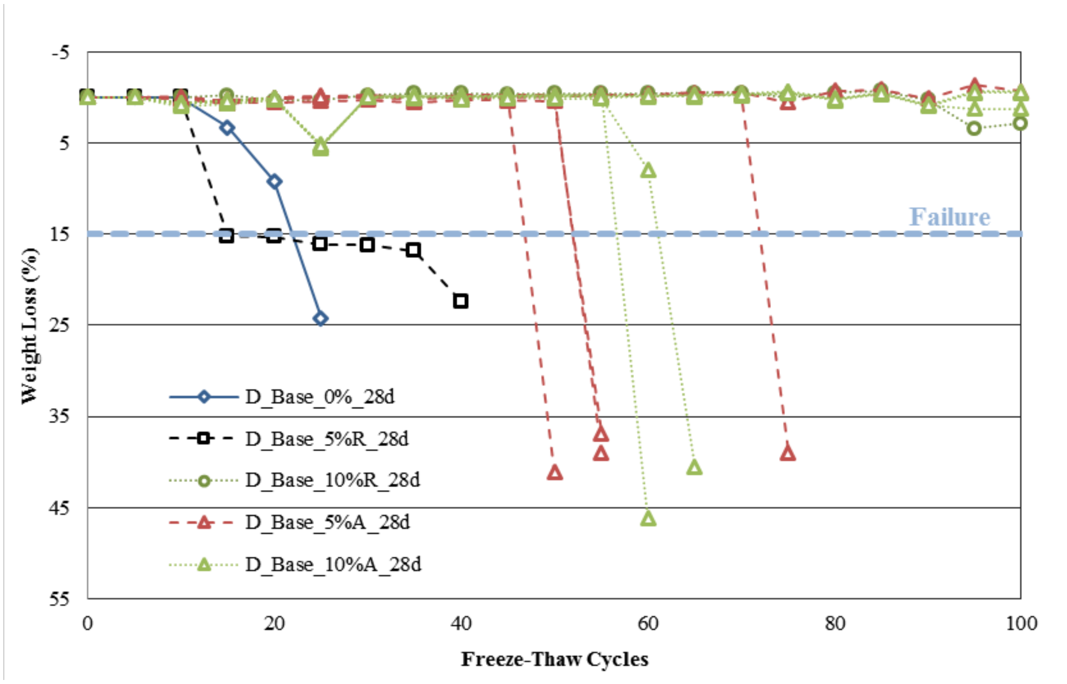

Figure 3.4 - UVM 8% Salt Sol. - Effects of Sand

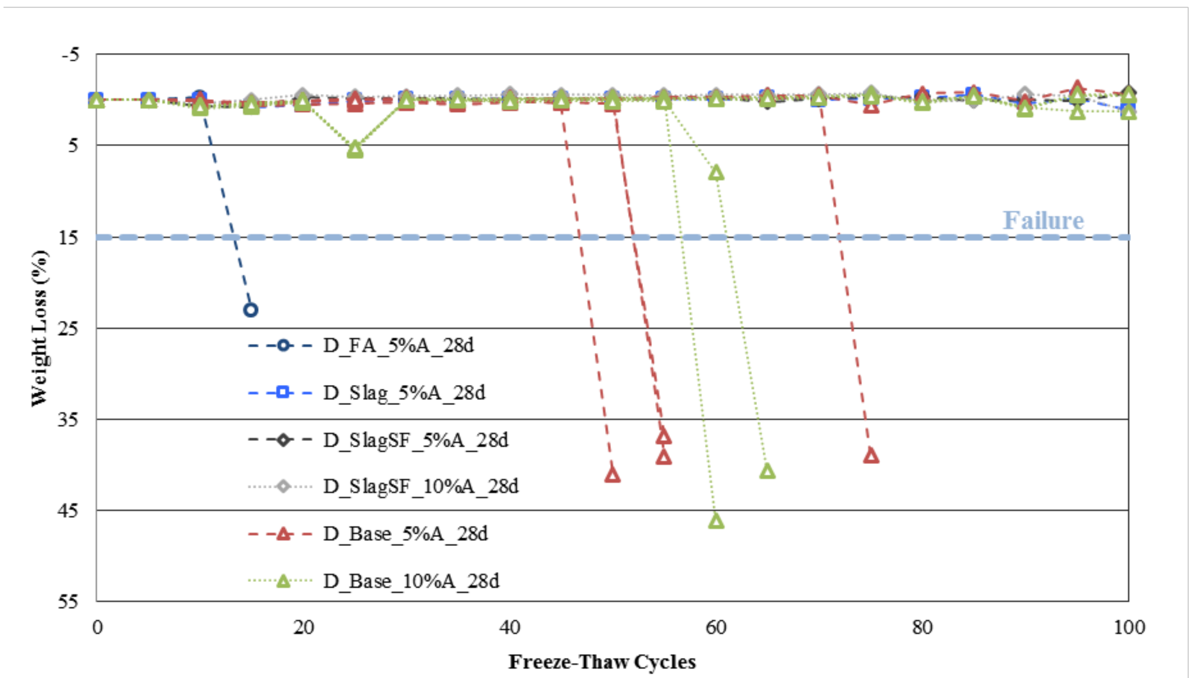

Figure 3.5 - UVM 8% Salt Sol. - Effects of Cement Replacements

Figure 3.6 shows the results from slag and fly ash mixes with varied curing duration. Fly ash samples at 7 and 28 day curing failed before 20 days. The fly ash samples cured at 54 days remained intact till 85 days. The results of testing with fly ash show that the samples had low freeze-thaw durability. Specimens with slag cured at 7 days failed within 20 days of testing, showing more curing time is needed. Specimens with slag cured for 28 and 54 days passed the full 100 day testing, indicating they had good durability, and adequate curing at 28 days.

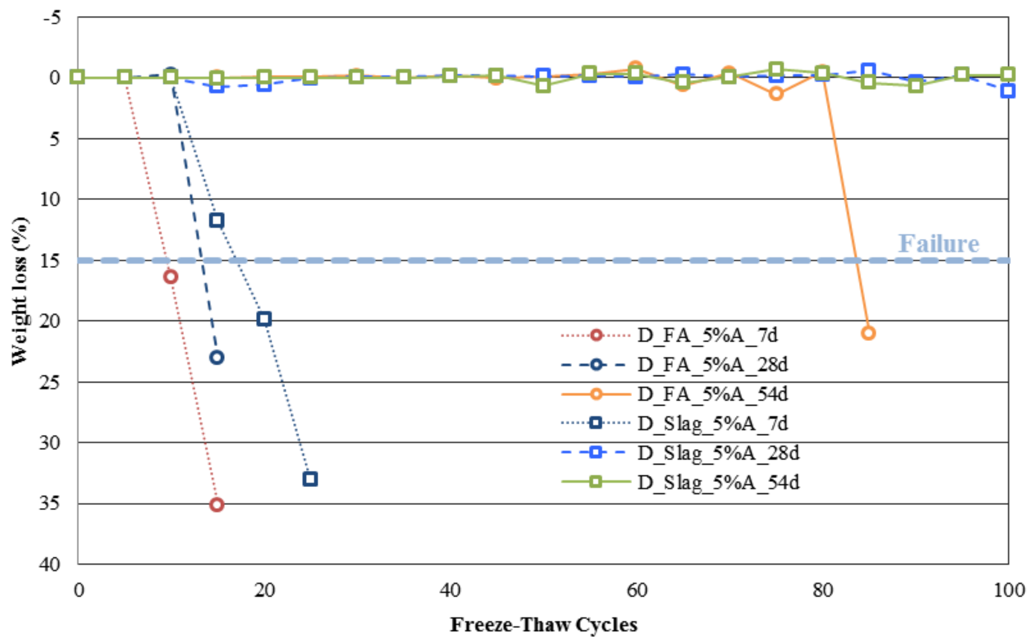

Figure 3.6 - UVM 8% Salt Sol. - Effects of Curing in Cement Replacements

The freeze-thaw testing at Norwich University was done to test the use of salt guard, with the following mix designs: Slag, 5% sand addition, 28 day curing and Slag, 10% sand addition, 28 day curing. Three sets of each mix design were sprayed with salt guard and put through 100 freeze-thaw cycles in 0%, 4%, and 8% salt solutions. The same tests were performed on specimens dipped in salt guard. All specimens (dipped in or sprayed with salt guard) survived the 100 freeze-thaw cycles with less than 3% mass loss, as seen in Figure 3.7. Because all the base samples, those without the salt guard application also remained intact through 100 cycles of freeze-thaw, it is unclear if salt guard will increase durability.

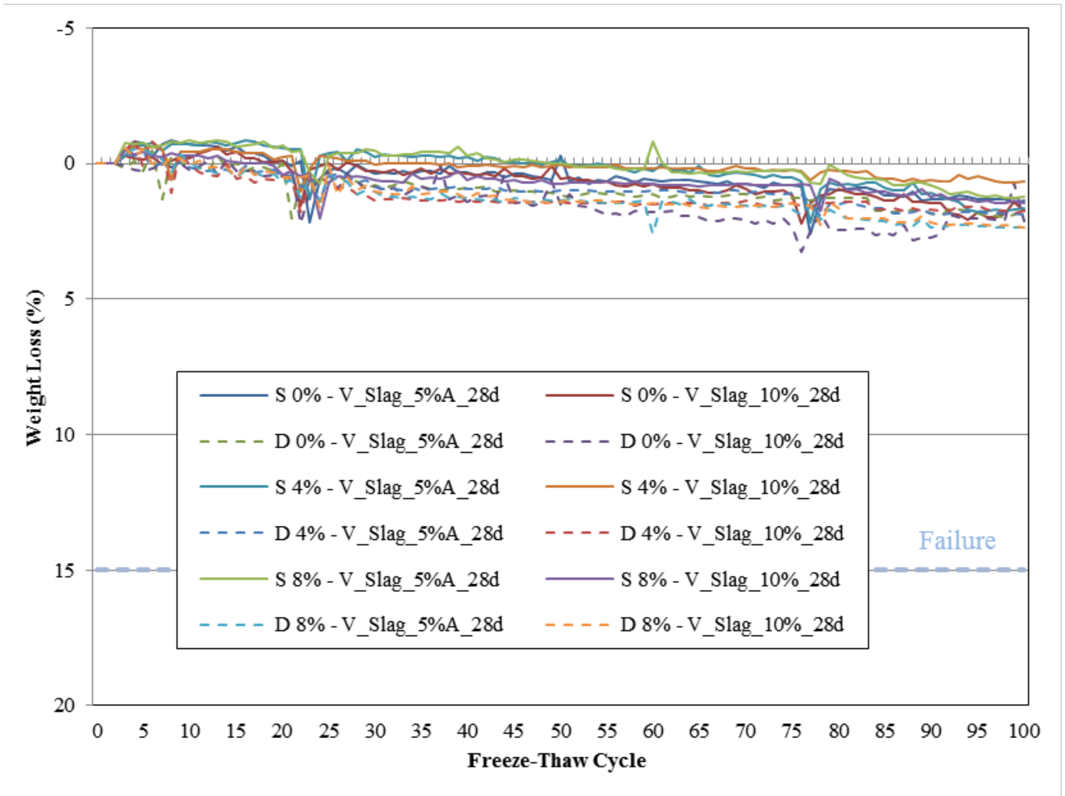

Figure 3.7 - Norwich Salt Guard - All Mixes

3.4 CONCLUSIONS

A series of laboratory tests on pervious was conducted to evaluate the replacing of conventional portland cement binder with a more suitable mix design to counter the damages that come from freeze-thaw and deicing salts. The mix designs were tested for freeze-thaw durability, with exposure to salt solutions. The pervious concrete specimens were tested using a modified freeze-thaw procedure, to approximate field conditions. Testing included one freeze-thaw cycle per day for up to 100 days, with the samples allowed to drain during freezing.

The effects of sand addition, sand replacement, fly ash, slag, silica fume; and curing time on the durability of pervious concrete were investigated. In addition to freeze-thaw resistance with and without salt, void ratio, hydraulic conductivity, and compressive strengths of the various mixes were also evaluated, and found to be within acceptable ranges for pervious concrete. It was hoped that the inclusion of sand would reduce the damage caused by freeze-thaw cycles. Sand replacement at 10% did show good durability to freeze-thaw. The results found from cementitious replacements, performance of these replacements under varying curing times and salt guard application provided some new information. The following specific conclusions could be drawn from this study (for the specific mix design investigated):

- Pervious concrete specimens showed minimal degradation when tested for freeze-thaw durability with water without any deicing salt for 100 days of one freeze-thaw cycle per day.

- Pervious concrete is more durable in controlled freeze-thaw environments (with exposure to 8% salt solution) with cement replacements such as slag and slag/silica fume than with solely type II cement or fly ash replacement.

- Pervious concrete using 20% cement replacement with fly ash needs increased curing time to perform well in harsh (8% salt solution) freeze-thaw testing. Otherwise, the cement paste damage is seen in a few freeze-thaw cycles.

- Pervious concrete with 20% cement replacement with slag can perform sufficiently well in a controlled freeze-thaw test, when cured beyond 7 days, and has good durability at the standard 28 days curing.

- A 10% sand replacement improved freeze-thaw durability, while 5 and 10% sand addition, and 5% replacement did not.

- Salt guard, both dipped or sprayed, may help improve freeze-thaw durability in a 100-cycle test. Additional testing is needed to determine if the salt guard helped the sample’s durability, as the base mix without salt guard application also lasted the full 100 day testing cycle.

CHAPTER 4

4.1 RECOMMENDATIONS FOR FUTURE WORK

Recommendations for future work include:

- The results reported here showed some variability. Additional efforts to develop laboratory methodologies that yield very consistent laboratory specimens of pervious concrete would be desirable.

- Testing should be targeted to lower void contents of pervious concrete, to test the mix designs with denser samples, and to achieve greater compressive strength.

- Salt guard should be tested on weaker mixes (e.g. without sand and slag) or in harsher environment to examine if it improves the durability of pervious concrete.

- The testing conducted has determined new pervious concrete mix designs that showed improved freeze-thaw durability in the slow freeze-thaw testing. The successful components of the current testing should be combined and thoroughly tested in an experimental field application.

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