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16. Abstract

Concerns persist regarding pervious concrete durability in cold climates related to freeze-thaw and exposure to salt. This study was conducted as an extension to previous work regarding pervious concrete in Vermont, to further investigate freeze-thaw durability with salt exposure in a laboratory environment representative of field conditions. Pervious concrete specimen variations included the addition of sand, replacement of cement with slag, replacement of cement with slag with silica fume, curing time, and saltguard treatment.

The addition of 5% sand improved freeze-thaw durability, while the addition of 10% sand led to decreased workability, density, and durability. Both the slag and slag with silica fume cement replacements improved the freeze-thaw durability in comparison to the cement only base mix. Curing time (7 to 56 days) did not influence freeze-thaw durability of pervious concrete with slag or slag with silica fume replacement. The application of liquid saltguard treatment for freeze-thaw resistance was found to be best performed using a dipping procedure over spraying the surface of the pervious concrete.

Considering the results of the current work as well as previous work regarding pervious concrete conducted at the University of Vermont and Norwich University, the following general conclusions are drawn which may assist in future pervious concrete mix designs and treatments. In general, the presence of sand replacing a small portion of coarse aggregate (up to about 10%) seems to improve freeze-thaw durability of pervious concrete. Adding sand to a mix design without making adjustments to water-to-cement ratio and other ingredients will most likely be not beneficial, as adding sand makes the cement ratio lower, resulting in decreased workability, and lower densities. Replacing up to 20% of Portland cement with slag or slag with silica fume also appears to have benefits in improving freeze-thaw durability of pervious concrete. Use of slag or slag with silica fume seem to yield better durability than using fly ash as cement replacement. It is likely that incorporating both sand replacement and cementitious alternatives (slag and slag with silica fume) may represent a more durable pervious concrete mix. If precast pervious concrete slabs were to be used, longer curing times and coating the slabs with saltguard may prove to be beneficial; however, any environmental concerns associated with the latter need to be investigated in future studies.

17. Key Words Pervious Concrete Pavement Concrete Mix Design Material Properties Freeze-thaw durability Winter maintenance	18. Distribution Statement No Restrictions

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EXECUTIVE SUMMARY

Pervious Concrete (PC) has performed as pavement successfully in regions without extended winter freezing. Vermont, however, endures relatively long freezing winters with a mix of precipitation requiring rigorous winter roadway maintenance. Progress has been made to address PC deterioration in a deicing salt environment, while concerns remain regarding clogging by sanding and foreign debris. This study was conducted as an extension to previous work regarding PC in Vermont, to further investigate freeze-thaw durability of PC with salt exposure in a laboratory environment representative of field conditions. PC specimen variations included the addition of sand, replacement of cement with slag, replacement of cement with slag with silica fume, curing time, and saltguard treatment.

The addition of 5% sand improved freeze-thaw durability of PC, while the addition of 10% sand led to decreased workability, density, and durability. Both the slag and slag with silica fume cement replacements improved the freeze-thaw durability in comparison to the cement only base mix. Curing time (7 to 56 days) did not influence freeze-thaw durability of PC with slag or slag with silica fume replacement. The application of liquid saltguard treatment for freeze-thaw resistance was found to be best performed using a dipping procedure over spraying the surface of PC.

Considering the results of the current work as well as previous work regarding PC conducted at the University of Vermont and Norwich University, the following general conclusions are drawn. In general, the presence of sand replacing a small portion of coarse aggregate (up to about 10%) seems to improve freeze-thaw durability of pervious concrete. Adding sand to a mix design without making adjustments to water-to-cement ratio and other ingredients will most likely be not beneficial, as adding sand makes the cement ratio lower, resulting in decreased workability, and lower densities. Replacing up to 20% of Portland cement with slag or slag with silica fume also appears to have benefits in improving freeze-thaw durability of PC. Use of slag or slag with silica fume seems to yield better durability than using fly ash as cement replacement. It is likely that incorporating both sand replacement and cementitious alternatives (slag and slag with silica fume) may represent a more durable pervious concrete mix.

Overall recommendations for VTrans:

Moving forward, an improved mix design with a small amount of sand (up to 10%) as a replacement of coarse aggregate and replacement of up to 20% Portland cement with either slag or slag with silica fume is worth considering. Saltguard treatment is promising; however, possible environmental impacts of using saltguard on PC need to be investigated.

It is worth considering using very well-made precast PC slabs that may allow much better quality control (e.g. extended curing time, dipping in saltguard) and quality assurance (e.g. uniformity, target void content, durability). In comparison to cast-in-place PC, precast PC slabs may allow removal and replacement as needed as part of routine maintenance.

Typically, PC has orders of magnitude higher initial infiltration capacity than what is needed, even for a 100-year rainfall; however, it also makes it prone to clogging.

Therefore, it is worth to consider sacrificing some initial infiltration capacity to gain durability, which may in turn help reduce clogging.

PC pavements are more suitable for sites with reasonably pervious subsurface and relatively deep (in excess of 10 ft) groundwater tables.

Rather than building the entire lot of PC, a combination of asphalt and PC may facilitate longevity.

Regardless of poured versus precast PC, the use of deicing salts results in damage during freeze-thaw. Therefore, the application of salt should be avoided, delayed, or at a minimum limited. Regular maintenance should be performed to prevent clogging, and ensure the continued performance of the pervious surface. Clogging initiates structural deterioration in freeze-thaw and salt environment. Ideally vacuuming and/or pressure washing would be used at least once a year and preferably more often.

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DISCLAIMER

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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) assess the effects of concrete ingredients (e.g. sand) on the resistance to freeze-thaw and deicing salts; (3) evaluate some admixtures/treatments (e.g. slag, slag with silica fume) to determine if they improve freeze-thaw and salt exposure durability of pervious concrete; (4) assess how curing time affects freeze-thaw durability of pervious concrete; and (5) determine how saltguard affects resistance to freeze-thaw and deicing salts. This scope of research was developed by a technical committee including personnel from Vermont Agency of Transportation, university researchers, and industry representatives. 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;
- assess how the presence of sand affects compressive strength, hydraulic conductivity and freeze-thaw durability of pervious concrete;
- determine how cement with slag and slag with silica fume affects compressive strength, hydraulic conductivity and freeze-thaw durability of pervious concrete;
- examine how curing time affects freeze-thaw durability of pervious concrete; and
- examine how salt guard affects freeze-thaw durability 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. Conclusions and recommendations for future research are presented in Chapter 4.

CHAPTER 2 - LITERATURE REVIEW

2.1 Background

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 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). Additionally, the US Green Building Council includes pervious pavements as a beneficial system in its Leadership in Energy and Environmental Design (LEED®) version 4 program, with credits available in stormwater management - rate and quantity, as well as stormwater management - quality control (Ashley, 2008). 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, 2002).

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, allow cement paste to properly coat aggregate particles, delay initial curing time, and ensure proper hydration during curing.

The study presented here investigated using sand, slag, and slag with silica fume in pervious concrete mix designs. Some background related to the use of these materials in pervious concrete is presented below.

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 while maintaining workability. 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, 2015). 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 content of the pervious concrete compared to a mix with only coarse aggregates (Schaefer et al., 2006; Kevern; 2009; Kevern; 2008a). Sand addition showed increased freeze-thaw resistance in some studies (Schaefer et al., 2006; Kevern, 2008a, b). 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; Kevern et al., 2008a, b). Sand is included in pervious concrete mixes using one of two mix design methods, either replacing a portion of the coarse aggregate with sand, or simply adding the sand to the mix and leaving the amount of coarse aggregate unchanged. Industry representatives in the Northeast U.S. have indicated sand addition is the primary method of sand inclusion in pervious concrete locally. Several studies have used the sand replacement strategy, while others have used sand addition (e.g., Schaefer et al., 2006; Kevern et al., 2008a and b).

2.4.3 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; FHWA, 2016). 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 (GGBFS) is both cementitious and pozzolanic. GGBFS 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, sulfate resistance, and increased compressive and flexural strength when compared to unblended Portland cement. Slag, with a lower relative density than Portland cement, also increases the volume of cement paste of slag blended concrete. GGBFS has been included in weather resistant pervious concrete used as a pavement overlay, replacing up to 35% of Portland cement. (Kevern et al., 2009)

2.4.4 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 and decreases porosity of the paste, providing resistance to sulfate attack. A large amount of silica fume (>7%) in concrete decreases workability, increases compressive strength, decreases permeability, and provides resistance to sulfate attack and alkali-silica reaction. Silica fume replacement has been found to be helpful for pervious concrete freeze-thaw durability under water cured conditions, but not when air curing is allowed (Kevern et al., 2008a and b, 2009; Yang, 2011).

2.5 ENGINEERING PROPERTIES OF PERVIOUS CONCRETE

2.5.1 Void content

Void content 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 content 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 content 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 content. It has been shown that void content 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 content.

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 the 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 been 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 content (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 excellent for stormwater collection. Hydraulic conductivity is directly related to the size and amount of voids present in pervious concrete. Hydraulic conductivity increases with increasing void content, decreasing water to cement ratio, decreasing compaction, increasing aggregate to cement ratio, decreasing unit weight, and decreasing fine aggregate (Ghafoori and Dutta, 1995; Park and Tia, 2004; Tennis et al., 2004; Wanielista and Chopra, 2007; McCain and Dewoolkar, 2010). A major concern in pervious concrete is its potential to clog, losing its infiltration capacity (Suozzo and Dewoolkar, 2012 and 2014).

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 pervious concrete pavements. 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 pervious concrete pavement (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 C666, 2008). 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, 2008a). Other investigations have studied adding admixtures and fibers or changing the water to cement ratio, coarse aggregate, and moisture conditions (Ghafoori and Dutta, 1995; Schaefer et al., 2006; Wang et al., 2006; Yang et al., 2006; Kevern et al., 2008b; 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 pervious concrete pavements 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. (2009) suggests 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 (Yang et al., 2006; Kevern et al., 2008b) and have no effect in slow cycles (Yang, 2011). Kevern et al. (2008a) 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 et al., 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 (2015) showed that in a one cycle per day freeze-thaw testing, salt application at 8% produced the greatest damage.

2.6.6 Salt Guard

Saltguard is a general-purpose saline/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. Saltguard is commonly used to reduce spalling of new conventional concrete surfaces due to freeze-thaw cycling. The chemicals react with concrete and masonry components leading to longer lasting protection. The compound penetrates deeply for maximum protection, and seals pores and capillaries of substrate preventing liquid absorption while allowing excellent vapor transmission. Saltguard exceeds National VOC Emission Standards for Architectural Coatings 40 CFR Part 59 (< 600 g/L). Saltguard is generally applied with a low pressure, airless sprayer.

2.6.7 Time of Curing

Time allowed for conventional concrete to cure is commonly known to yield higher compressive strengths with increased curing time. Additionally, salt attack on cement paste both during and after concrete curing is always of concern. Knowledge of the effects of curing time with regards to freeze-thaw and chemical attack on pervious concrete is largely lacking. Therefore, the time a pervious concrete mix is allowed to cure in a saturated lime bath before being subjected to freeze-thaw and salt exposure is investigated in this study at 7, 28, and 56-days.

CHAPTER 3 - EXPERIMENTAL PROGRAM AND RESULTS

3.1 Experimental Investigation

The current investigation was intended to continue research based on findings from previous work pertaining to pervious concrete resistance to freeze-thaw and salt chemical attack in mixes typically used in Vermont, where freezing temperatures are common, and salt is extensively used as a deicer (Anderson and Dewoolkar, 2015; Anderson et al., 2015). Pervious concrete specimens were prepared and tested in the laboratory, with an effort to balance representing field conditions with producing consistent, repeatable results. Previous work has indicated specimen consistency is difficult to achieve, therefore all specimens were prepared using common laboratory, equipment, materials, and procedures. Common procedures included specimen construction, curing, and testing. Specimens were tested for hydraulic conductivity, void content, compressive strength, and freeze-thaw resistance with salt exposure. Freeze-thaw testing was performed using slow daily cycles, salt exposure, and allowing full drainage during freezing instead of the procedures outlined in ASTM C666. This slow drained freeze-thaw procedure is believed to better replicate field conditions for pervious concrete durability (NRMCA, 2004; Yang, 2006; ACI, 2010; Anderson and Dewoolkar, 2015; Anderson et al., 2015).

3.2 Mix Design and Specimen Preparation

The pervious mix designs tested in this study were based on a mix design used at the Park and Ride site in Randolph, Vermont, constructed in 2008, and used in previous studies (McCain and Dewoolkar, 2010; Suozzo and Dewoolkar, 2012 and 2014; Anderson and Dewoolkar, 2015; Anderson et al., 2015). Variations to this mix were agreed upon by a technical committee including personnel from the Vermont Agency of Transportation, industry, and universities (University of Vermont and Norwich). All mixes used the same 3/8 inch (10 mm) crushed ledge coarse aggregate. Fine aggregate used in select specimens was all from the same source and met ASTM C33 *Standard Specifications for Concrete Aggregates* specifications (ASTM C33, 2008). Care was taken to fully dry all aggregates in laboratory air using large flat pans and airflow until materials were visibly dry before mixing. Type I-II Portland cement was used throughout. Chemical admixtures included a high range water reducer (HRWR), air entraining agent (AEA), hydration controlling admixture (HCA), and viscosity modifying admixture (VMA). Slag used was ASTM C989-05 Grade 120, while densified silica fume used meet ASTM C1240 *Standard Specification for Silica Fume Used in Cementitious Mixtures* requirements. Specific mix designs are summarized in Table 1 (ASTM C1240, 2010).

Table 1 – Pervious Concrete Mix Designs Used in this Study

Mix Design	Cement lbs/yd^3 (kg/m^3)	Water lbs/yd^3 (kg/m^3)	Aggregate lbs/yd^3 (kg/m^3)	Sand lbs/yd^3 (kg/m^3)	Slag lbs/yd^3 (kg/m^3)	Silica Fume lbs/yd^3 (kg/m^3)	Admixtures oz/ft3 (ml/m^3)
base	610 (362)	167 (99)	2,792 (1,656)				AEA: 0.074 (77) HRWR: 0.689 (719) VMA: 2,360 (2.3) STAB: 2.26 (2360)
5% sand	610 (362)	167 (99)	2,792 (1,656)	150 (89)			
10% sand	610 (362)	167 (99)	2,792 (1,656)	300 (178)			
slag	490 (290)	167 (99)	2,792 (1,656)		120 (71.3)		
slag with silica fume	464 (275)	167 (99)	2,792 (1,656)		116 (68.8)	30.5 (18.1)	

All pervious concrete specimens were cast in 10.2 cm (4-inch) diameter by 15.2 cm (6-inch) tall cylinders. Concrete mixing generally followed ASTM C192 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* with the following exceptions (ASTM C192, 2007). Specimens were constructed using a drop compaction method. This drop compaction entailed filling the mold half full with wet concrete and dropping the mold 2.5 cm (1-inch) onto a solid surface 10 times to densify the mix. The mold was then slightly overfilled and dropped 10 more times. Excess material was struck from the top of the mold or extra material was added to the mold and struck using a flat edge steel blade.

Specimens were then cured in laboratory air, held at 20°C (68°F), for one day with a damp cloth over the top of the molds. After one day, the specimens were submerged into a lime saturated water bath for the duration of timed curing. Water baths were located in the laboratory with a maintained temperature of 20°C (68°F). Once cured for the specific duration, specimens were removed from the lime bath and dried and stored in laboratory air until further testing commenced. At this point conventional performance properties were measured, including hydraulic conductivity, and void content. Additionally, five specimens from each mix design were tested for compressive strength. The application of saltguard to specimens was conducted using one of two methods. The "sprayed" application of saltguard entailed 5 sprays with a handheld spray bottle on the top surface of the specimens. Specimens "dipped" in saltguard were immersed in a bowl of saltguard twice, slowly. Freeze-thaw testing specimens were then labeled and stored in laboratory air until all samples were cured and ready for freeze-thaw testing.

3.3 Testing Methods

3.3.1 Hydraulic Conductivity, Void content, and Compressive Strength Testing

Hydraulic conductivity and void content were measured for all specimens, taking the average of three trials after timed measurements were observed to have stabilized, indicating all air was removed from the pervious concrete specimen. Compressive strength was tested for five specimens from each mix design and curing duration.

Hydraulic conductivity was measured generally following a falling head procedure presented by Olek and Weiss (2003). Using this procedure, a pervious concrete specimen is placed and saturated in a latex membrane within a ridged cylindrical mold forming the falling head permeameter. The time for water to pass through the specimen allows the calculation of the hydraulic conductivity

Void content was determined generally following ASTM C1754 *Standard Test Method for Density and Void Content of Hardened Pervious Concrete (ASTM C1754, 2012)*. Using this procedure, the void content is calculated by comparing the weights of the oven dried specimen to the weight of the same specimen submerged in water.

Compressive strength was determined using ASTM C39 *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimen (ASTM C39, 2009).* Elastic caps were used in compression testing in accordance with ASTM C1231 *Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete*

Cylinders (ASTM C1231, 2008). Testing for compressive strength was performed within three days of removing the specimens from the lime bath at the end of their respective curing durations.

3.3.2 Freeze-Thaw Testing

To better simulate conditions in the field, specimens were subjected to a single freeze-thaw cycle per day for up to a total of 100 freeze-thaw cycles. Failure was considered to be 15% or greater mass lost. To start the freeze-thaw cycle, each specimen was twice dipped and vigorously shaken in an 8% saline solution. The salt concentration of 8% was found to be most damaging in previous testing (Anderson and Dewoolkar, 2015). As the specimens were removed from the solution they were shaken again in open air and placed on tilted trays and allowed to drain. Salt solution was replaced every other cycle, and as needed throughout the testing. After all specimens were dipped, shaken, and drained in this fashion, they were then placed into a commercial freezer. The first specimen dipped, shaken, and left to drain was the first moved into the freezer each cycle. In this fashion, all specimens were allowed the same warm draining time on the tilted trays, approximately 15 minutes. In the freezer, specimens were placed on grates allowing free drainage for the duration of the freeze cycle. After 16 hours in the freezer at -16°C (3°F), specimens were removed, weighed, and placed on the tilted trays for the duration of the thaw cycle, 8 hours daily at 20°C (68°F). At this point specimens had completed the freeze-thaw cycle, and were ready to begin the next cycle. Typically, five individual pervious concrete specimens composed a mix design, curing time, or saltguard treatment specimen group.

3.4 Experimental Results and Discussion

3.4.1 Basic Properties

The typical properties were measured to qualitatively ensure pervious concrete mix designs performed as intended. Properties assessed were specimen density, void content, hydraulic conductivity, and compressive strength. Density and compressive strength values are typically the average of five specimens per mix design, and hydraulic conductivity and void content are the average of three repeat tests on three specimens per mix design. It is common to see relationships between these properties, where a mix with high void content will generally have high hydraulic conductivity, and low density and compressive strength. The study of basic properties shall be observed in two separate discussions: the effects of sand addition at 28-days curing, and the effects of cement replacements with varying curing times. The average engineering properties of all specimens included in the basic properties study are summarized in Table 2.

Table 2 – Summary of Average Engineering Properties

Mix Design	Curing (days)	Average Density pcf (kg/m^3)	Average Void Content (%)	Average Hydraulic Conductivity in/hr (cm/s)	Average Compressive Strength psi (MPa)
base	7	112.7 (1,805)	32.6	4,086 (2.88)	735 (5.07)
	28	119.5 (1,901)	26.6	3,382 (1.90)	1,691 (14.26)
	56	120.2 (1,925)	24.1	2,646 (1.87)	1,895 (13.07)
5% sand	28	116.7 (1,869)	28.9	3,733 (2.63)	1,106 (7.62)
10% sand	28	112.0 (1,794)	27.9	2,797 (1.97)	577 (3.98)
slag	7	109.1 (1,748)	32.6	4,938 (3.48)	616 (4.25)
	28	119.9 (1,850)	26.7	3,036 (2.14)	2,144 (9.47)
	56	119.9 (1,921)	26.9	2,856 (2.02)	1,985 (13.69)
slag with silica fume	7	111.6 (1,787)	31.8	4,085 (2.88)	784 (5.40)
	28	118.5 (1,820)	25.2	2,353 (2.17)	1,924 (8.47)
	56	115.5 (1,850)	28.7	2,729 (1.93)	1,541 (10.62)

3.4.1.1 Basic properties – effects of sand addition

For the current discussion regarding the effects of sand addition, the top three mixes within Table 2, cured for 28 days, are to be concentrated on (base - 28-day, 5% sand, and 10% sand addition). The hydraulic conductivity was found to be high for the specimens included in this study with an average of 2.33 cm/s (3,304 in/hr), above typical readings of 0.2 to 1.2 cm/s (280 to 1,680 in/ hr). Void contents ranged between 26.6% and 28.9%, which are in the middle of the typical range of 18-35% (NRMCA, 2004; Tennis, 2004;

ACI, 2010). The average compressive strength deceases as the percentage of added sand increases, with a marked decrease at the 10% sand addition level, again concentrating on the 28-day curing specimens. This trend in compressive strength corresponds with lower densities observed as sand was added, as seen in Figure 1, particularly at the 10% sand addition level.

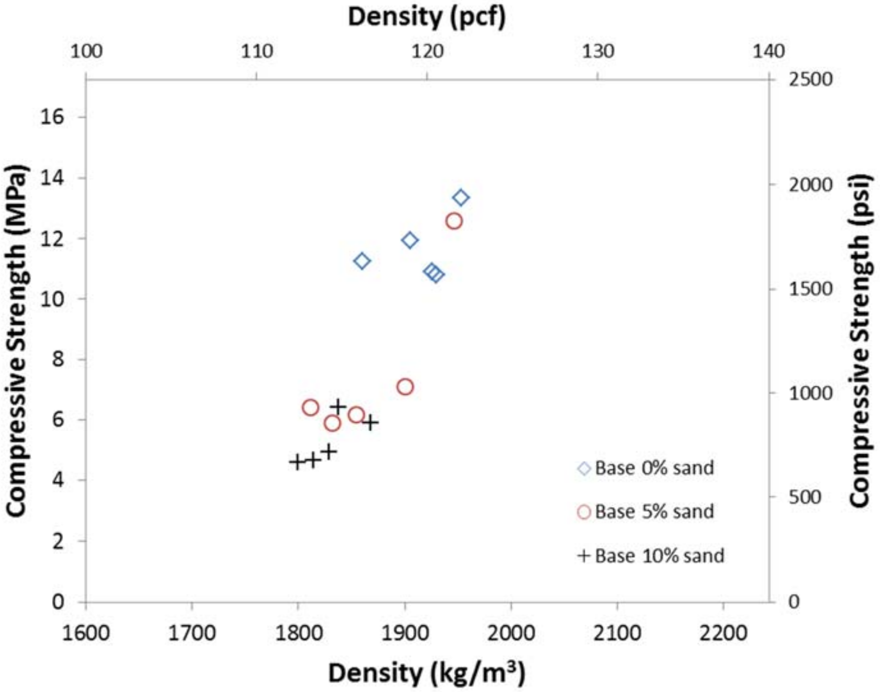

Figure 1 – Effects of Sand Addition on Compressive Strength

During the mixing and specimen preparation portion of the current study it was observed that when adding sand, the mix tended to become less workable. This decreased workability was thought to be due to a portion of the paste being taken to coat the sand, particularly at the higher percentage sand. Also, when mixing the 10% sand addition specimens, it was observed that some of the paste was essentially pasting sand particles together, making rounded pods of cemented sand. These higher sand percentage mixes were dryer and less workable during sample compaction (energy held constant for all sample compaction), leading to lower densities and lower compressive strengths.

3.4.1.2 Basic properties – effects of cement replacement and curing time

The environmental by-products replacement of Portland cement portion of this study, observed the effects of mass replacement using a slag and a slag with silica fume combinations. These replacement mixes were compared with a mix using Portland cement alone, termed the “base” mix. Each of these mixes were duplicated in three batches of ten specimens to observe the effects of curing time on each mix design, whereby a batch of ten specimens was cured for 7, 28, and 56-days for each mix design. Five of these sets of ten specimens were included with this basic properties study, while five were used in freeze-thaw testing for each curing time.

As seen in Figure 2, higher void contents were generally observed to correspond with higher hydraulic conductivities as is typical for pervious concrete (Tennis, et al., 2004). As seen in Figure 3, the densities of specimens in their mix design groups varied by up to 160 kg/m^3 (10 pcf) indicating some variability using the dropping compaction method, likely corresponding to workability. The compressive strengths of these drop compaction specimens were within the typical range of 3.45-27.6 MPa (500-4,000 psi), however, they were consistently in the lower end of this range. As seen in Table 2, the average compressive strengths increased with increased density, as is expected of pervious concrete (NRMCA, 2004). The base mix showed a steady increase in strength (and density) with increased curing time, while mixed results were observed for the slag and slag with silica fume specimens. Both slag and slag with silica fume specimens showed a decrease in compressive strength at 56-day curing, along with a slight decrease in density. For all mixes, 7-day curing had notably low compression strength, with higher strengths at curing times of 28-days and above.

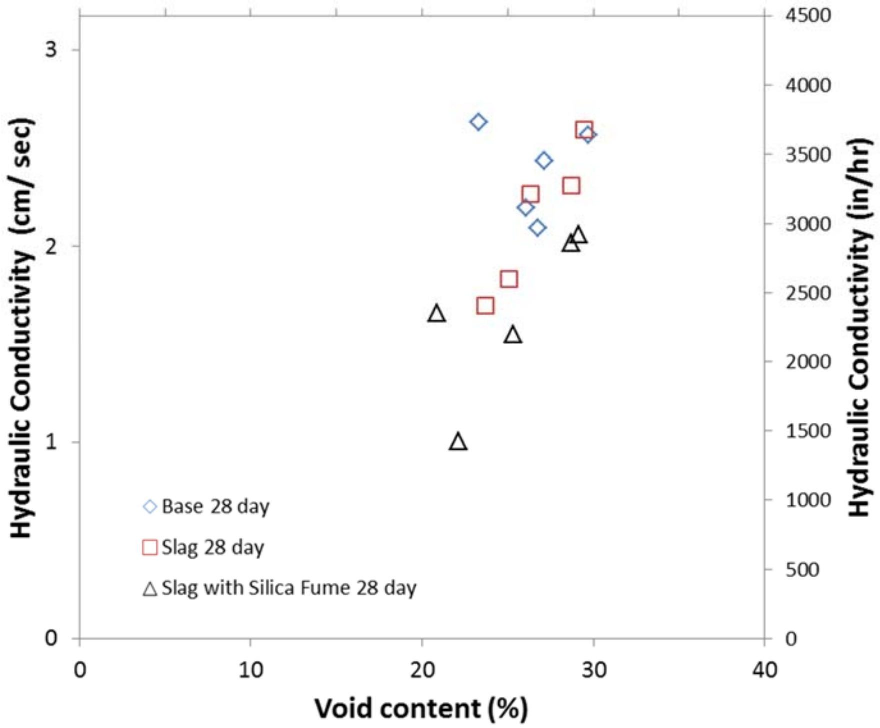

Figure 2 – Effects of Cement Replacements on Hydraulic Conductivity

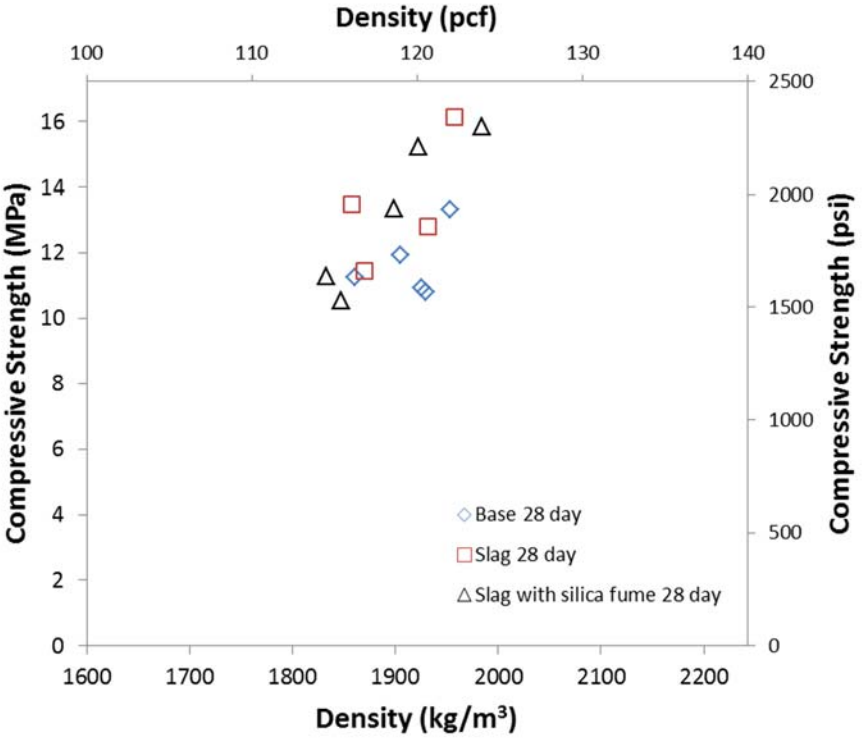

Figure 3 – Effects of Cement Replacements on Compressive Strength

3.4.2 Durability to freeze-thaw and salt exposure

Testing results and discussion regarding freeze-thaw durability using a slow drained, 1-day cycle with daily 8% salt water bath immersion are presented below. Five mix designs were investigated including a base mix with 0% sand, base mix with 5% sand addition, base mix with 10% sand addition, slag replacement of a portion of the Portland cement, and slag with silica fume replacement of a portion of the Portland cement content. Three different durations of curing were investigated for base mix, slag, and slag with silica fume mix designs including 7, 28, and 56-day curing in a saturated lime bath. Additionally, a liquid saltguard product was tested using two application techniques on all five mix designs at 28-day cure. Only specimens tested in freeze-thaw are included in the calculation of sample properties included here. This freeze-thaw testing included just under 100 specimens.

3.4.2.1 Freeze-thaw durability – effects of sand addition

Figure 4 presents the results of freeze-thaw testing with 8% salt solution on pervious concrete specimens cured for 28-days with 0%, 5%, and 10% sand. These did not have saltguard treatment. Of the 15 specimens tested in freeze-thaw, the only specimen observed to have failed the 100 cycle freeze-thaw test is a base mix specimen. The specimen that failed exhibited the lowest density of the 0% sand specimens at 1,892 kg/m^3 (118.1 pcf). Specimens containing sand at 5% and 10% were all below this density, except one 10% sand sample at 1,893 kg/m^3 (118.2 pcf). Given that the 5% and 10% sand specimens were of lower density, and all survived the 100-cycle freeze-thaw testing, indicates that the addition of sand likely helped with freeze-thaw durability even while densities decreased with sand addition.

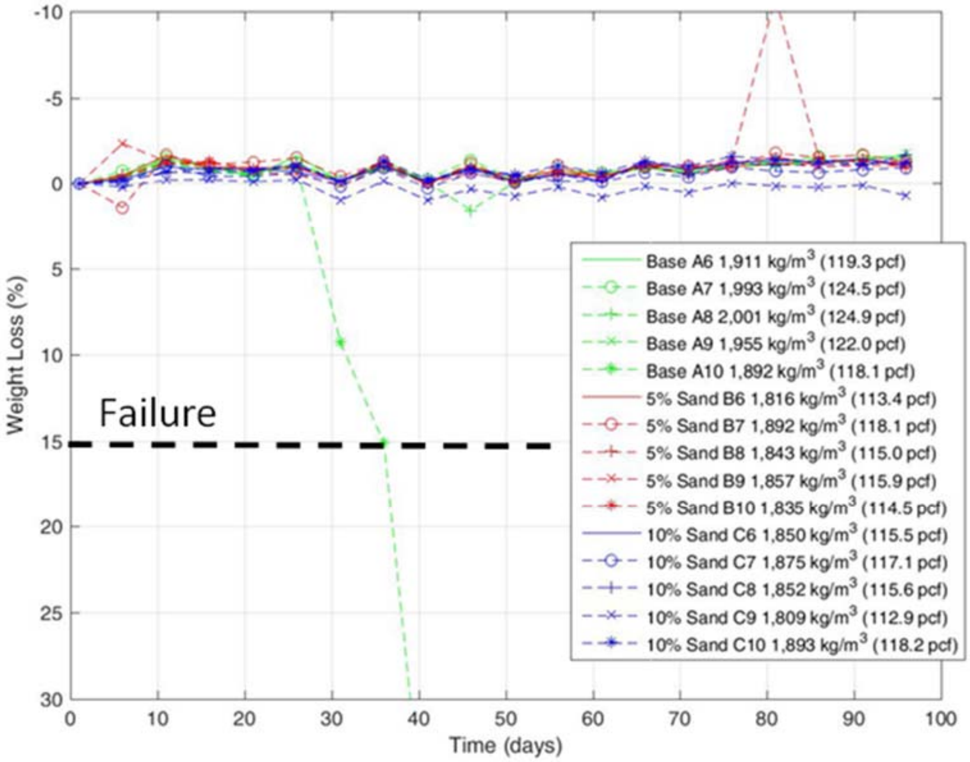

Figure 4 – Sand Addition 28 Day Cure Freeze-Thaw Results

3.4.2.2 Freeze-thaw durability – effects of cement replacement and curing time

Table 3 summarizes average properties of pervious concrete specimens and freeze-thaw failure statistics for the set of tests that investigated the effects of curing time (7, 28, and 56-days) and cement replacement (base, slag, and slag with silica fume). This freeze-thaw testing included 41 individual pervious concrete specimens.

All cement replacement specimens, including slag, and slag with silica fume, endured the full 100 cycles of freeze-thaw with salt bath testing for all three curing times. For the base mix, two specimens of five failed for the 7-day cure, while one specimen of five failed, for each of the 28 and 56-day cures. Cement replacement specimens were of equal or lower average densities than the base mix samples, further indicating the cement replacements were effective durability adjustments.

Table 3 – Time of Curing and Cement Replacement Freeze-Thaw Results

Mix Design	Curing Time (days)	Average Density pcf (kg/m^3)	Average Void Content (%)	Average Hydraulic Conductivity in/hr (cm/s)	% Survived Freeze-Thaw
base	7	110.6 (1,772)	33.4	3,445 (2.43)	60%
	28	121.8 (1,951)	25.6	2,751 (1.94)	80%
	56	121.9 (1,952)	23.1	2,551 (1.80)	80%
slag	7	110.6 (1,772)	33.5	4,464 (3.15)	100%
	28	119.0 (1,907)	26.8	3,291 (2.32)	100%
	56	119.8 (1,918)	26.4	2,894 (2.04)	100%
slag with silica fume	7	110.9 (1,776)	32.1	4,334 (3.06)	100%
	28	118.6 (1,900)	25.4	2,366 (1.67)	100%
	56	117.5 (1,882)	27.2	2,387 (1.68)	100%

This curing time study indicates that replacement of some cement with slag, as well as slag with silica fume, creates a more robust pervious concrete that resists freeze-thaw testing well, regardless of time allowed to cure in lime saturated water. The base mix alone represents the mix design where less curing time led to decreased freeze-thaw durability. Here the 7-day cure exhibited two of five specimens failing, while one of five specimens failed for both 28 and 56-day cures.

3.4.2.3 Freeze-thaw durability – effects of saltguard treatment

Table 4 summarizes average properties of pervious concrete specimens and freeze-thaw failure statistics for the set of tests that investigated the effects of saltguard treatment (sprayed and dipped). All five mix designs were treated in this manner (base, 5% sand, 10% sand, slag, slag with silica fume) cured to 28-days. This portion of the study included 69 specimens.

Table 4 – Saltguard Freeze-Thaw Summary

Mix	Saltguard application	Average density pcf (kg/m^3)	Average void content (%)	Average permeability in/hr (cm/sec)	% Survived freeze-thaw
base	none	121.8 (1,951)	25.6	2,751 (1.94)	80%
	sprayed	115.3 (1,847)	30.1	3,489 (2.46)	100%
	dipped	116.2 (1,862)	29.4	2,969 (2.10)	100%
5% sand	none	115.4 (1,848)	30.4	4,183 (2.95)	100%
	sprayed	121.8 (1,951)	27.1	2,815 (1.99)	100%
	dipped	121.7 (1,949)	27.7	3,117 (2.20)	100%
10% sand	none	115.9 (1,856)	30.1	3,775 (2.66)	100%
	sprayed	110.9 (1,776)	33.3	2,776 (1.96)	0%
	dipped	109.5 (1,754)	33.3	3,206 (2.26)	0%
slag	none	119.0 (1,907)	26.8	3,291 (2.32)	100%
	sprayed	108.8 (1,743)	33.4	3,200 (2.26)	0%
	dipped	106.7 (1,709)	34.8	3,802 (2.68)	100%
slag with silica fume	none	118.6 (1,900)	25.4	2,366 (1.67)	100%
	sprayed	111.9 (1,792)	31.2	3,228 (2.28)	100%
	dipped	112.7 (1,805)	33.1	3,262 (2.30)	100%

First, concentrating on the one base mix specimen that was found to fail during freeze-thaw testing, the following observations can be made. For the base mix, lower densities were observed for specimens from both methods of saltguard application, as compared to the untreated specimens. These lower densities are thought to relate to the time the mix was standing while other specimens were being cast. The only specimen to fail during freeze-thaw testing was untreated by saltguard. All saltguard treated specimens happened to have lower densities, yet they survived the full 100 freeze-thaw cycles. For the base mix, saltguard treatment had a positive effect, overcoming decreased densities, allowing specimens to survive the full 100 freeze-thaw cycles.

All specimens with 5% sand addition survived the full freeze-thaw testing sequence. Average densities were 1,849 kg/m^3 (115.4 pcf) for untreated specimens and 1,949 kg/m^3 (121.7 pcf) for all saltguard treated specimens. Furthermore, all individual 5% sand specimens exhibited densities above 113.4 pcf (1,816 kg/m^3). These 5% sand specimens were observed to form a solid matrix with the sand evenly distributed with the paste surrounding the larger aggregate particles.

Specimens included in the 10% sand pervious concrete mix were consistently of lower density than both the base mix, and the 5% sand specimens. As stated earlier, this is thought to be due to a portion of the paste being consumed, essentially pasting sand particles together into small pods, leading to thinner paste coverage of coarse aggregate in the mix. All untreated 10% sand specimens were observed to survive the full 100-cycles. While, all specimens treated with saltguard, both sprayed and dipped, failed during freeze-thaw testing. It is thought that the excessively low densities exhibited by the specimens treated with saltguard contributed to the low durability, as seen in Figure 5. This set is the only case where any specimens dipped in saltguard failed in freeze-thaw testing, losing more than 15% of their original mass.

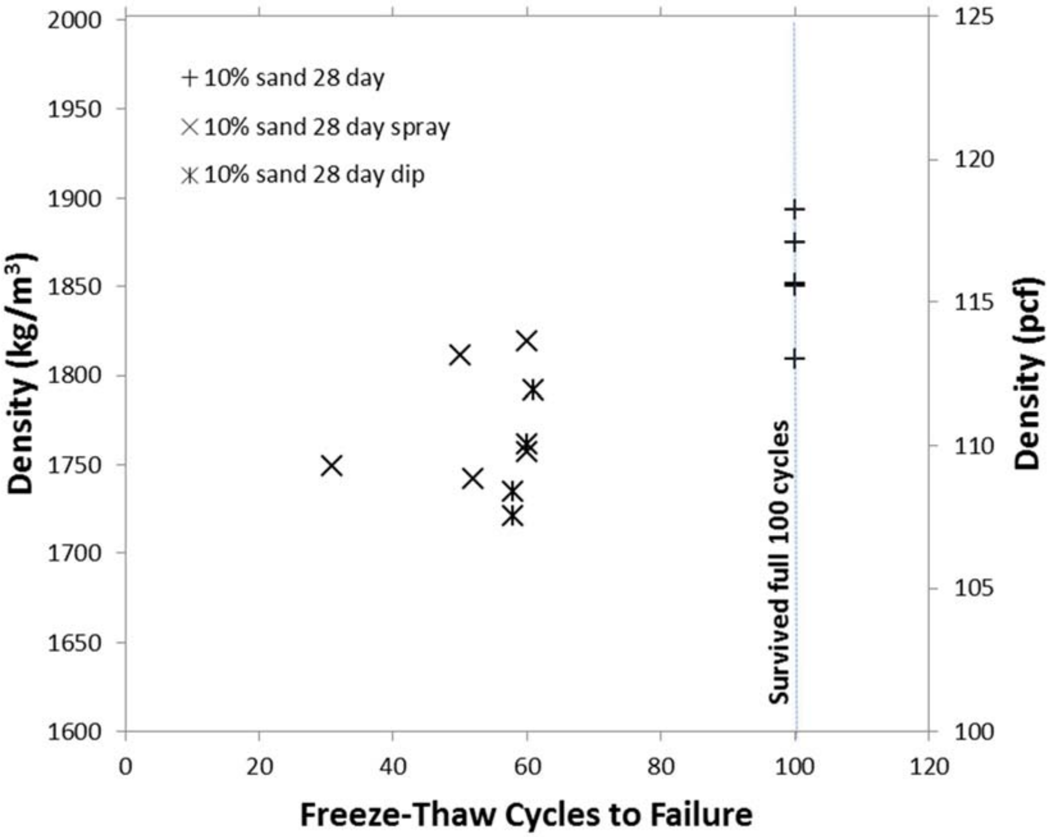

Figure 5 – 10% Sand Saltguard Treated Freeze-Thaw Results

Slag replacement specimens form an interesting set when looking at freeze-thaw results with respect to saltguard application. Figure 6 depicts freeze-thaw results with a comparison of specimen densities for the slag mix design. All five slag specimens left untreated survived the 100 freeze-thaw cycles, with specimen densities between 1,858 and 1,938 kg/m^3 (116 and 121 pcf). Meanwhile, every specimen treated with saltguard sprayed onto the specimen failed within the 100 freeze-thaw cycles, with densities ranging from 1,650 to 1,810 kg/m^3 (103 to 113 pcf). Interestingly, all the specimens dipped in saltguard survived freeze-thaw testing even with a density range between 1,650 and 1,746 kg/m^3 (103 and 109 pcf), and the lowest average density of this set. In this case dipping specimens appears to be a better application method for saltguard than spraying the saltguard onto one of the surfaces of the specimens.

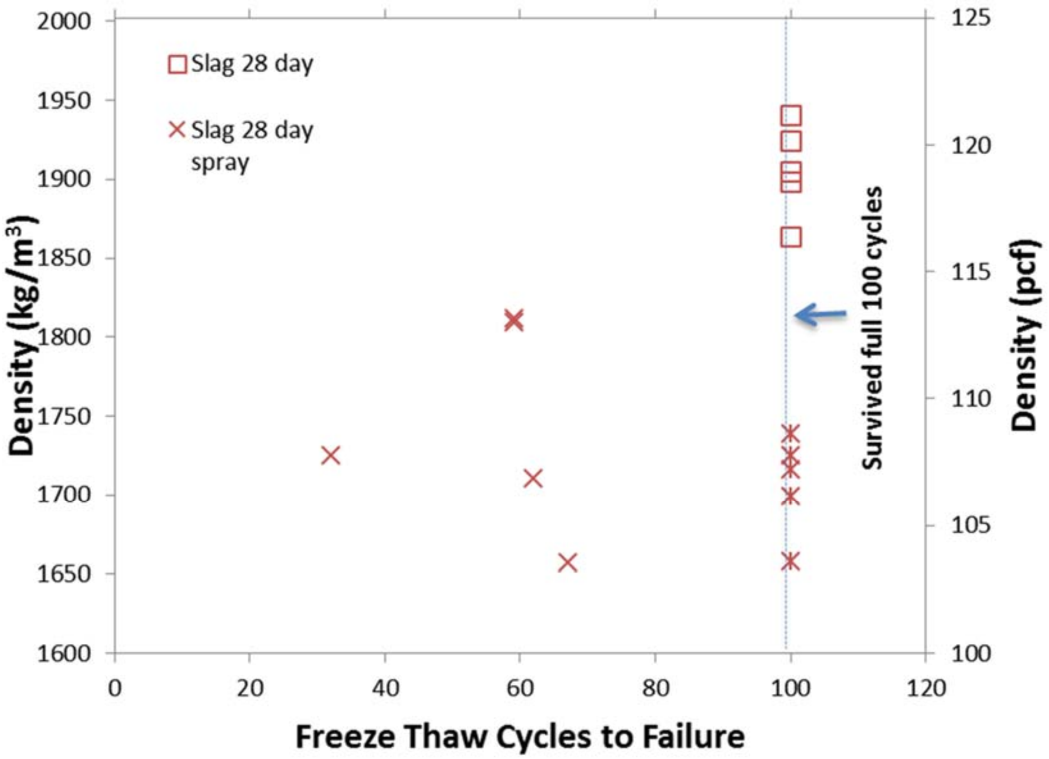

Figure 6 – Slag Saltguard Treated Freeze-Thaw Results

All slag with silica fume specimens endured the full 100-cycle freeze-thaw sequence. Again, specimens treated with saltguard had lower density than untreated specimens. All saltguard treated specimens were below 1,738 kg/m^3 (108.5 pcf) and endured the full 100-cycle freeze-thaw testing indicating slag with silica fume is a good cement replacement material and saltguard treatment may assist with freeze-thaw durability.

CHAPTER 4 - CONCLUSIONS AND FUTURE RECOMMENDATIONS

4.1 Conclusions from Presented Research

A laboratory investigation was performed in an effort to identify pervious concrete mix designs that are durable in winter weather and a harsh deicing environment. Specimens were subjected to freeze-thaw durability using a slow (one cycle per day to up to 100 cycles) procedure. This procedure incorporated drained conditions during freezing and an 8% salt solution exposure each cycle. This procedure was intended to better simulate field conditions and expose specimens to the harshest salt concentration. Five mix designs were investigated including a base mix, 5% sand addition, 10% sand addition, slag replacement of cement, and slag with silica fume replacement of cement. The effects of the curing time on the durability of pervious concrete were also investigated. The effects of applying liquid saltguard to pervious concrete on its durability were also investigated. This set of testing was supplemented with void content, hydraulic conductivity and compressive strength testing. Variables tested were agreed on by a panel of personnel from Vermont Agency of Transportation, local industry representatives, and university researchers before testing commenced. The following conclusions were drawn from this study:

- The addition of 5% sand to pervious concrete resulted in specimens with good freeze-thaw durability throughout this study.
- The addition of 10% sand to the pervious concrete mix led to decreased workability, yielding decreased sample densities in this study. Decreased density was seen to result in decreased durability. The mix design displayed both good resistance to freeze-thaw with salt exposure in instances with higher densities, as well as weakness to freeze-thaw with low densities.
- Slag and slag with silica fume replacement of a portion of the Portland cement created pervious concrete specimens that resisted the full 100-cycles of freeze-thaw testing with the sole exception of low density sprayed with saltguard slag replacement specimens.

- The curing time in a saturated lime bath (7, 28, and 56-day) did not affect the freeze-thaw performance of the slag replacement, or slag with silica fume replacement mix designs. All specimens survived the full 100 freeze-thaw cycles with 8% salt exposure regardless of curing time allowed in the saturated lime bath before storage in laboratory air until freeze-thaw testing.
- When applying liquid saltguard, fully dipping the pervious concrete appears to be superior to spraying the surface of the concrete for freeze-thaw durability. In practice, this method is feasible if precast pervious concrete slabs can be dipped in saltguard and then placed in the field. Environmental implications of saltguard-treated pervious concrete placed in the field must however be investigated before adopting saltguard for field applications.
- The density of pervious concrete appears to be important for freeze-thaw durability with exposure to 8% salt solution. Specimens below approximately 1,842 kg/m^3 (115 pcf) appear to be at increased risk of freeze-thaw failure, irrespective of sand inclusion, slag replacement, slag with silica fume replacement, or saltguard application.
- Constant energy compaction led to varying densities and freeze-thaw results throughout the mix designs tested.

4.2 Conclusions from Prior Previous Concrete Research in Vermont

Research on pervious concrete has continued in Vermont since about 2008. Key findings from these previous studies are included here for completeness.

- 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 with 10% and 20% cement replacement with fly ash showed greater freeze-thaw durability.
- Of the 0%, 2%, 4%, 8% and 12% salt concentrations examined, the 8% salt concentration was found to be harshest.

- Pervious concrete is more durable in controlled freeze-thaw environments (with exposure to 8% salt solution) with cement replacements such as slag and slag with silica fume.
- Replacing a portion of coarse aggregate with sand seems to be more effective than simply adding sand to the mix design.
- Compaction in a laboratory setting using a three dimensional vibration table was found to result in excessive migration of paste to the bottom portion of the sample.
- Key components causing freeze-thaw damage include high saturations and high salt concentrations. Any clogging of pores in presence of salt and cold temperatures accelerates damage.

4.3 Recommendations for Practice

Considering the results of the current work as well as previous work regarding pervious concrete conducted at the University of Vermont and Norwich University, the following general conclusions are drawn which may assist in future pervious concrete mix designs. Note that this as well as most of the previous pervious concrete work performed by the authors used variations of the mix design used at Randolph Park and Ride facility in Randolph, Vermont.

- In general, the presence of sand replacing a small portion of coarse aggregate (up to about 10%) seems to improve freeze-thaw durability of pervious concrete. Adding sand to a mix design without making adjustments to water-to-cement ratio and other ingredients will most likely be not beneficial, as adding sand makes the cement ratio lower, resulting in decreased workability, and lower densities. Because of this, replacement of a portion of the coarse aggregate is preferred.
- Replacing up to 20% of Portland cement with slag or slag with silica fume also appears to have benefits in improving freeze-thaw durability of pervious concrete.
- It is likely that incorporating both sand replacement and cementitious alternatives (slag and slag with silica fume) may represent a more durable pervious concrete mix.

- If precast pervious concrete slabs were to be used, longer curing times and coating the slabs with saltguard may prove to be beneficial; however, any environmental concerns associated with the latter need to be investigated in future studies.
- Use of slag or slag with silica fume seem to yield better durability than using fly ash as cement replacement.
- Placement of pervious concrete in the field should be scheduled in the early summer to maximize curing time before exposure to freezing temperatures and deicing chemicals.
- Efforts should be made to cover pervious concrete immediately after placement for seven days to prevent excessive drying during initial cure.
- The use of deicing salts results in damage during freeze-thaw, its application should be avoided, delayed, or at a minimum limited.
- Regular maintenance should be performed (perhaps twice a year) to prevent clogging, and ensure the continued performance of the pervious surface. Ideally vacuuming would be used.
- Monitoring should continue on existing pervious concrete pavements, to observe structural and hydraulic performance as time progresses.

4.4 Recommendations for Future Research

Based on the presented research and previous work performed on pervious concrete in Vermont, the following suggestions are made for future research:

- Development of a method of constructing cylindrical pervious concrete laboratory specimens that creates consistent and measurable density and void structure during specimen construction that are representative of field conditions is recommended. A strategy of compacting cylindrical specimens in two lifts incorporating the drop compaction used here, with a measurement and densification plate on top of the material that can be monitored for exact density during sample construction is suggested.

- Further investigation examining saltguard should focus on dipping pervious concrete into the saltguard solution.
- Investigate the environmental risks of placing saltguard precast pervious concrete panels in the field.
- Laboratory freezing during freeze-thaw cycles with salt solution should be maintained at or below -3 degrees Fahrenheit.
- Variation of compaction effort and density to freeze-thaw resistance and strength in a field representative environment should be investigated.
- A study comparing laboratory versus field pervious concrete composition would also be very beneficial.

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