Report No. UT-25.07

SUPPLEMENTARY CEMENTITIOUS MATERIALS FOR CHLORIDE RESISTANCE OF BRIDGE DECKS

Prepared For:

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Final Report
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RESEARCH

Keeping Utah Moving

Utah Department of Transportation - Research Division
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16. Abstract

The purpose of this report is to present the measured properties and comparison between concrete mixtures consisting of different available supplementary cementitious materials (SCMs) for the purpose of understanding which SCM provides the best chloride resistance for bridge decks in Utah. The concrete batches were created in the Utah Valley University laboratory, with the original mix design aimed at replicating the proportions used in the Salt Lake City Airport parking garage constructed in 1990. This original design consisted of 9% of the replacement of cement by a silica fume. The recreated mixtures consisted of up to 15% replacement of cementitious content. The SCMs studied including three types of silica fume found across the country, two fly ash sources, a local pozzolan, and a locally collected waste glass dust. A control with no SCMs was also created for comparison. Properties measured were slump, unit weight, air content, compressive strengths at 7 and 28 days, and rapid chloride permeability after 1 year age. Overall, the study showed the silica fume mixtures outperformed in strength and rapid chloride permeability significantly over the other SCMs.

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AC	Absorption Capacity
ASR	Alkali Silica Reaction
BYU	Brigham Young University
CH	Calcium Hydroxide
C-S-H	Calcium-Silica-Hydrate
FA	Fly Ash
FHWA	Federal Highway Administration
OPC	Ordinary Portland Concrete
PCC	Portland cement Concrete
PT	Post-Tensioned
PU	Ultrafine Pumice
RCPT	Rapid Chloride Permeability Test
SCM	Supplementary Cementitious Material
SF	Silica Fume
SFC	Silica Fume Concrete
SLC	Salt Lake City
UDOT	Utah Department of Transportation
U of T	University of Toronto
UVU	Utah Valley University
WG	Waste Glass Powder or Dust
WR	Water-Reducer

EXECUTIVE SUMMARY

In 1989, a parking garage at the Salt Lake City airport was constructed using silica fume concrete to ensure chloride resistance. The initial concrete design for the garage proposed 7.4% silica fume and 15% class F fly ash as replacements for cement. However, prior to construction, the design was modified to 9% silica fume and without any fly ash, to meet rapid chloride specifications. This was the first structure in Utah utilizing silica fume. The parking garage was inspected, with samples and cores collected and evaluated at 12 and 29 years of service life. Experts from the initial design, construction, and maintenance of the garage were interviewed to gather more insights about the structure. Overall, the structure remained in excellent condition and was found to have minimal chloride penetration.

One of the main reasons for the uniqueness of the parking garage project was the use of silica fume as a supplementary cementitious material (SCM) for reducing chloride ion ingress. Silica fume has not been utilized in other infrastructure projects in Utah likely because the material is expensive, reduces workability, and causes a sticky finish. The purpose of this report is to provide measured property, particularly chloride resistance data, associated with concrete that uses SCMs. The mixtures for this report included: 1) replicated mixture of the parking garage with silica fume as a pozzolan, and 2) mixtures containing other pozzolans available to the Utah Department of Transportation.

Products and suppliers have changed over time, so this report gives a good baseline of how available products compare. The silica product used in the 1989 airport parking lot was a new additive material at its time. The same supplier of silica is no longer on the market. Instead, this report compares three silica fume products that are currently available. Also, since most projects in the state of Utah utilize a class F fly ash as an SCM, this report also looks at two current suppliers of this class F fly ash. There are other SCMs that were locally available at the time this project was performed, and these are also investigated. In summary, the pozzolans or supplementary cementitious materials selected included: three brands of silica fume, two sources of class F fly ash, a local ultrafine pumice, and a locally collected waste glass dust. Trial mixtures were created at Utah Valley University with replacements of cement at 9% silica fume or at 15% of other SCMs (a higher dosage for the other SCMs was utilized to emphasize the benefits of these other SCMs).

Fresh properties and strength values measured in this research matched what was expected based on other research studies with similar SCMs. For example, the silica fume mixtures had a lower slump than a control batch of no SCMs and the same water-reducer and water content. Fly ash mixtures and those with glass dust had significantly higher slump levels. Strengths were highest with silica fume concrete reaching over 8000 psi after 28 days. Most important to this research study were the results regarding assessing these mixtures in the rapid chloride permeability test. The testing for rapid chloride penetration was done at Brigham Young University in a blind test (SCMs in each cylinder were not shared with the student doing the measurements). The silica fume mixtures at 9% by far exceeded the chloride resistance of the other pozzolans. Pumice and waste glass dust as SCMs did the same or worse than the control mixture of no SCMs, in terms of chloride resistance.

Discussion is added to this report regarding other considerations on the financial impact, constructability, and on the environment related to these pozzolans. This discussion is meant to provide guidance to UDOT on selecting an appropriate SCM for future bridge decks. Overall, this study found the use of silica fume concrete is highly recommended for long-term durability and chloride resistance of bridge decks.

1.0 INTRODUCTION

1.1 Problem Statement

There is a projected need in the construction market to use alternative supplementary cementitious materials (SCMs), compared to the use of fly ash as an SCM. An opportunity presented itself to investigate the in-service performance of a supplementary cementitious material known as “silica fume,” a.k.a. “microsilica” or “silica flour.” This SCM has been expensive but proven in studies to provide superior density resulting in high strength and excellent durability against ion ingress.

A parking garage at the Salt Lake City (SLC) airport was built with silica fume concrete (SFC) in 1989 and demolished in 2020. Prior to demolition, core samples were taken, and non-destructive evaluations were measured. Specifically of interest was quantifying if and how much chloride ions had penetrated in the structure with the use of the silica fume. Based on the results from the in-situ testing on the SLC parking garage, the chloride resistance was higher in the parts of the structure containing silica fume (Pratt, 2024).

This report focuses on assisting the Utah Department of Transportation (UDOT) in utilizing currently available SCMs in achieving similar low chloride penetration on bridge decks or other infrastructure exposed to deicing salts. To achieve this, first, an attempt was made to replicate the SFC mix design of the airport parking garage of 1989. Second, was to create mixtures with other SCMs of comparable dosage rates. Finally, all mixtures were evaluated for chloride resistance according to ASTM C1202 to determine which provided similar levels of chloride resistance. For consistency, basic fresh properties and strength were measured on each mixture as well. The SCMs investigated were three sources of silica fume, two sources of class F fly ash, a local ultrafine pozzolanic pumice, and a locally collected waste glass dust.

1.2 Project Background

This project was a small part of a larger project that started with the SLC airport parking garage. The whole project was funded by UDOT and the American Concrete Institute (ACI) Foundation. This portion of the project was completed as part of a senior capstone project at

Utah Valley University (UVU) and as a research project with graduate students at Brigham Young University (BYU).

1.2.1 Salt Lake City Airport Parking Garage Details

The first silica fume concrete structures in the United States were built in the 1980s. Among them was the parking garage for the SLC International Airport built from 1989 to 1991. The parking garage contained a 9% micro silica slurry. It had a 75-year design life (Hooton et al., 2010) but was demolished after 29 years of use to make way for a new airport in 2020.

The parking garage consisted of a ground floor, three suspended levels, two helix ramps, and a bridge deck and ramp leading to the first suspended level. The ground floor was a slab on ground (SOG) that was made from ordinary concrete without silica fume or reinforcement. The suspended levels, helix ramps, and bridge deck were made from SFC and contained epoxy-coated reinforcing bars ranging from No. 4 to No. 7 in size, as well as post-tensioned (PT) members. A top view of the parking garage can be seen in Figure 1.1.

Figure 1.1 Top View of Old Parking Garage at SLC Airport Taken from Google Images Before the Structure was Demolished.

1.2.2 Salt Lake City Airport Parking Garage's Concrete Mix Design

Information on the concrete mix design for the airport was anecdotal. Details were gathered with the assistance of ACI Intermountain Chapter in a meeting with representatives from the companies that built the garage. Reaveley Engineering designed the structure in 1989. Holcim (now owned as LafargeHolcim) provided the cement at the time of the parking garage construction. Geneva Rock provided the concrete for the original airport structure. PSI was the testing firm verifying the mixture properties.

A 7.4% silica fume and 15% fly ash were specified in the original drawings by Reaveley Engineers. However, a former employee of Geneva Rock indicated that because the rapid chloride penetration test specification could not be met with this mixture, the design was changed to eliminate fly ash and instead they used 9% silica fume. The silica fume was called "micro silica" at the time and mixed with water to create a slurry since its fine particle size may have tended to clump if added as a dry powder to the mixture.

The final water-to-cementitious (w/cm) ratio was stated to be 0.38. The air content was likely 7% plus or minus 1%. The mixture included a high-range water-reducer to increase workability. It also included a coarse-to-fine aggregate ratio of 0.38. A cylinder cast during the construction of the parking garage was tested after 28 days of wet curing, and the sample exceeded the machine's compressive strength capacity of 15,000 psi.

1.2.3 Salt Lake City Airport Parking Garage's In-Situ Evaluation

The garage's concrete slabs were crack mapped by hand using measuring tape by the UVU capstone team. The structure's crack densities were re-drawn into, and lengths and areas calculated, using AutoCAD. The results can be seen in Table 1.1 (Bordelon et al., 2021).

Table 1.1 Crack Densities of Salt Lake City Airport's Concrete Parking Garage

SLC Parking Garage Structure Type	Concrete Type	Reinforcement Type	Average Crack Density (ft/ft^2)
Ground Floor	Plain	None	0.0020
Entrance Bridge	Silica Fume	#7 epoxy-coated rebar and post-tension cables	0.095
Covered Suspended Slabs (1st to 3rd Level)	Silica Fume	#4 epoxy-coated rebar and post-tension cables	0.018
Helixes	Silica Fume	#4 epoxy-coated rebar and post-tension cables	0.043

The garage's crack densities were low compared to other structures in the United States (Bordelon et al., 2021), especially structures that undergo similar freeze-thaw cycles and deicing salts. It could not be determined if the use of silica fume made a difference in the low crack density. There were other factors that may have also contributed to the lower crack density, including the location in the structure relative to weather and traffic patterns, reinforcing size and spacing, post-tensioning stress level, thickness of the slabs, and annual maintenance.

The parking structure was measured from two different studies in its service life (at 12 and 29 years) to determine the chloride resistance, with results tabulated in Table 1.2. Through personal communication with Doug Hooton, the field cores SL-5 and SL-6 were estimated to be taken from the ground floor, which was plain concrete instead of silica fume concrete. For this reason, the measurement of 3032 coulombs from the reference Hooton et al. (2010) is shown here with the plain concrete.

Table 1.2 Rapid Chloride Permeability from Cores (Hooton et al., 2010; Pratt, 2024)

<table>
<tr><th rowspan="2">SLC Parking Garage Structure Type</th><th colspan="4">Charge Passed (Coulombs)</th><th rowspan="2">Permeability Class</th></tr>
<tr><th colspan="2">12 years' service life (Hooton, et al., 2010)</th><th colspan="2">29 years' service life (Pratt, 2024)</th></tr>
<tr><td>Ground Floor (Plain Concrete)</td><td>3032</td><td></td><td colspan="2">1343</td><td>Low</td></tr>
<tr><td>Entrance Bridge SFC</td><td></td><td></td><td>162</td><td>404</td><td>Very Low</td></tr>
<tr><td>Covered Suspended Slabs (1st to 3rd Level) SFC</td><td>623</td><td>787</td><td>772</td><td>1151</td><td>Very Low to Low</td></tr>
<tr><td>Helixes SFC</td><td></td><td></td><td colspan="2">1448</td><td>Low</td></tr>
</table>

Another indicator to estimate how chloride ions might migrate into the concrete is through electrical impedance. The electrical impedance was measured from several core samples taken within the structure, and the value of impedance normalized by the length of the core sample. The results are tabulated in Table 1.3. On average, plain concrete was found to have a normalized electrical impedance of 20,923 Ohm/in. while the silica fume concrete was found to be statistically higher at 94,589 Ohms/in. The low *p*-value indicated that the concrete containing silica fume, even after 29 years of service, was more resistant to electron ion flow, or less likely to have deicing chloride ions ingress.

Table 1.3 Electrical Impedance from Cores (Pratt, 2024)

Normalized Electrical Impedance (Ohm/in.)						
Concrete Type	**# Samples**	**Minimum**	**Maximum**	**Average**	**St. Dev.**	***p*-value**
Plain Concrete	3	18,724	23,924	20,923	2,691	0.0010
Silica Fume	16	27,091	271,343	94,589	72,147	

The SFC that made up the old parking garage at the airport was in excellent condition when it was demolished. The garage had very few delamination locations, and low crack densities for a parking garage structure (Bordelon et al., 2021). Of the few cracks that existed within the structure decks, many occurred during construction and were sealed. Cracks in the entrance ramp did exhibit higher chloride levels within the crack, but the surrounding SFC was still sound and had exceptionally low chloride ingress (Bordelon et al., 2021, Pratt, 2024).

1.3 Objectives

UDOT has implemented a chloride permeability test criteria for its bridge structures across the state. While not many structures contain silica fume due to its cost, the addition of having a pozzolan (fly ash, or other high silica product) can be found in most of the bridge decks as a material which achieves the low permeability requirements. This low permeability also leads to minimal maintenance or repair costs. In addition, the availability and future consistency of fly ash has been predicted to be a major issue for the construction industry (Caltrans 2016; Ley and

Cook, 2021), so other SCMs are needed. The objective of this study was to compare different SCMs in concrete in terms of the effect of the SCM on chloride resistance.

1.4 Scope

The following mixtures and measurements were made as the scope of this project.

Concrete Mixtures: A high strength SFC mix designed to include 9% silica fume by weight of cementitious material. The same mix was used, but with varying available silica fume products were created in comparison. In addition, other SCMs provided by local supplies and with the approval of the UDOT task group were studied. These other SCMs included 2 fly ash sources, a local ultrafine pumice, and a locally collected waste glass powder. Many of these other SCMs are reported to be effective in providing durability benefits at higher replacement rates, so these were all added at 15% by weight of cementitious material.

Fresh and Hardened Properties: Slump, unit weight, temperature, and pressurized air content were measured on each trial batch. Compression strength tests (7- and 28-day) were measured from 3-4 cylinders of each batch. Early trials were made to achieve comparable results to those of the airport parking garage. These were recorded in the appendix, but the trials with subpar strengths or workability were not evaluated for chloride resistance.

Chloride Resistance: Each successful batch was evaluated with the rapid chloride penetration test ASTM C1202 at BYU's laboratory. Duplicate samples were cut from the same cylinder of each mixture to provide statistical representation. Samples were evaluated at over 1 year of age.

1.5 Outline of Report

Section 2 of this report explains the materials that were used in the study based on literature, the manufacturer, or measured by the research team. All standard ASTM procedures were followed and the results from the successful batches can be seen in Section 3. Discussion on the selection and impact of these different SCMs is provided in Section 4. Overall findings and recommendations are found in Section 5. The Appendices provide material details from the manufacturers, raw data from all trial batches, and some photos of the samples.

2.0 RESEARCH METHODS

2.1 Overview

This section includes background literature, and the known properties associated with the different SCMs studied. The reported properties of the materials from the manufacturer or measured along with the mixture designs utilized, and listings of the test methods performed are also provided.

2.2 Materials

All the materials utilized in this study were approved through the UDOT technical advisory group and locally provided at the time of this study. Other materials may or may not be suitable for bridge deck projects but were not studied as part of this scope. The following is a list of the materials that were provided for this study scope:

- Type II/V Portland cement was provided by Todd Laker at LafargeHolcim out of Morgan, Utah.
- Coarse and Fine Aggregates were provided by Geneva Rock out of Draper, Utah.
- Three silica fumes were provided by 1) R.E.D. Industrial Products out of Grove City, Pennsylvania, 2) Euclid Chemical Company, and 3) GCP Applied Technologies.
- Two samples of Class F Fly Ash were provided by Doug Yeggy at Boral Resources from 1) Delta, Utah, and 2) Prairie States in Marissa, Illinois.
- The Ultrafine Pumice was provided by Brian Jeppsen from Hess Pumice Products out of Malad City, Idaho.
- Waste Glass Dust was collected from the glass recycling air filtration system by John Lair at Momentum Recycling out of Salt Lake City, Utah.

The following sections review the literature and properties known regarding each SCM material.

2.2.1 Silica Fume in Concrete

Silica fume is a by-product of silicon created from silica (quartz) and carbon (coal, coke, and wood chips). When heated, the mixture produces silicon and silicon dioxide gas. The silicon dioxide gas is oxidized and condensed into ultrafine particles called silica fume. Silicon factories were prohibited from releasing silica fume into the air. As a result, they began filtering it and, in 1980, started selling it to concrete companies. Since then, the concrete industry has utilized silica fume to enhance the performance of concrete (Fidjestøl & Dåstøl, 2020). Silica fume is reported to be four times the cost of Portland cement (Alhajiri and Akhtar, 2023). It is anticipated that this cost is a main inhibitor for why silica fume has not been more utilized in concrete mixtures today.

Silica fume is amorphous and chemically reactive with water and cement. Silica fume is classified as a pozzolanic material because of its high siliceous content (silica fume typically is about 90-100% SiO_2) and that it converts calcium hydroxide (CH), a product formed during the hydration of cement, into calcium silica hydrate (C-S-H) gel. The magnitude of CH reduced by 35% after 28 days of curing with the addition of 20% silica fume replacement of cement (Fanijo, 2019). The resulting C-S-H gel that forms from the CH reduction is what contributes to the strength and binding power of the cementitious matrix. This also densifies the mixture and improves other durability aspects like resistance to chloride ingress, alkali-silica rection (ASR) and freeze-thaw durability.

A unique aspect of silica fume is that it has extremely small particle sizes. Silica fume particles have a diameter of 0.02 to 0.04 mils (0.5 to 1 micrometer), or roughly 1/100 of the size of an ordinary Portland cement particle. Due to its small nature, silica fume reacts faster (more surface area for reactions to occur with smaller particle size), and the particles fill in the voids between cement particles or along interfaces of the aggregates. The smaller particles of the silica fume are what significantly densify the cementitious matrix and thus reduce any pathways for chloride ions or other ion contaminants to enter the concrete after it has cured. A downside of this smaller particle size is that this also contributes to a lower workability, and in this case also a "sticky" mixture. Companies using silica fume in the concrete find they require extra practice and training to become familiar with finishing the surface sufficiently.

A study performed by Detwiler and Mehta explored which property of silica fume, physical or chemical, gave SFC its high strength (1989). The study included a fine black carbon powder with the same particle size as silica fume but without chemical properties. After 28 days of moist curing, the SFC had a much higher strength than the black carbon concrete sample. This indicated it was the silica fume's chemical properties that made it so strong. Detwiler and Mehta also determined that this chemical reaction needs 28 days of curing to be fully effective.

Whiting et al. studied the effects of silica fume on the amount of drying shrinkage (2000). SFC bridge decks sometimes have a higher shrinkage cracking tendency. The study concluded that SFC needs either 1) seven days of moist curing, or 2) to contain less than 8% silica fume to reduce the amount of shrinkage cracking. Researchers in Kansas found lower chloride concentrations in bridge deck overlay sections of low crack density. They were not able to determine if silica fume was a contributing factor in the bridge deck chloride concentrations or cracking densities (Miller and Darwin, 2000; Lindquist et al., 2005).

Overall, silica fume is a fine amorphous silica powder that is proven to provide high concrete strength and density; however, the material comes at a higher cost, requires more training on finishing, and must be cured properly to be effective. The benefits of this SCM were explored further in this study by replicating the successful mixture containing 9% silica fume that was used at the SLC airport parking garage.

2.2.2 Fly Ash in Concrete

Fly ash is the by-product of burning coal to produce electricity. In the burning of coal, the ash particles that fly up with the flue gases are collected and sold as "fly ash." Fly ash as an SCM was first used in the United States in the 1940s. Since then, it has been a major component in concrete design across the nation (Ecosmart Concrete, 2021).

As a pozzolanic SCM, fly ash reacts with free CH to form additional C-S-H gel. Fly ash has particle sizes ranging from 0.4 to 4 mils (10-100 micrometers), similar in size to Portland cement. It also has a spherical shape which increases concrete's workability and decreases the amount of water needed in the concrete mix (American Coal Ash Association, 2003).

Saha (2018) studied the effects of class F fly ash in concrete at varying levels of replacement by volume. The study replaced Portland cement with 10, 20, 30, and 40% fly ash by volume then assessed the samples' compressive strengths after 7, 28, and 180 days of curing. The study concluded that fly ash decreased the early compressive strength of concrete by slowing down its hydration rate. The samples containing 30% and 40% fly ash were lower than the control's compressive strength after 28 days, but much higher after 180 days of curing. Fly ash needs time for the pozzolanic reaction to take place.

Class F fly ash has lowered the chloride permittivity measured at 28 and 180 days. Based on the test ASTM C1202 at 28 days, a 10% replacement of class F fly ash demonstrated a low chloride permeability level, and a higher replacement rate of 40% achieved a very low chloride permeability level (Saha, 2018). Class F fly ash has also been beneficial to reduce the expansion of ASR (Bordelon and Choletti, 2021; Saha et al., 2018) and a little more effective than class C fly ash, due to the lower calcium oxide content in class F.

2.2.3 Pumice in Concrete

Pumice is a natural pozzolan created from volcanos. During an eruption, the superheated rock is ejected, and under rapid cooling and depressurization internal bubbles of gas are released leaving behind the very spongy-looking structure. Pumice has been used for over 2000 years in concrete, often as a lightweight aggregate source. The pumice that is available closest to Utah is located in Malad City, Idaho.

The pumice in this study is classified as "Ultrafine Pumice" because it has been sieved to the particle sizes ranging from 0.55- 0.63 mils (14-16 micrometers), similar in size to ordinary Portland cement. At this particle size, again this natural product chemically reacts as a pozzolan. Studies on the effects of this ultrafine pumice on concrete were done at the University of Utah (U of U) and University of Texas-Austin (Ramasamy et al., 2017; Seraj et al., 2014). Both studies found that as an SCM, pumice concrete had lower compressive strengths than the control. Pumice also appeared to lower concrete's workability compared to Portland cement, such that higher dosages of a water-reducing admixture may be needed. The universities determined that the optimal replacement dosage for pumice is between 15% and 25% by weight of cementitious (Jeppsen, 2021).

The University of Texas-Austin (Seraj et al., 2014) evaluated the effects of pumice on chloride ingress based on electrical resistivity. The pumice concrete had a higher resistivity to chlorides than Portland cement. After 58 days, the control and pumice concretes had resistivities of 6.8 and 15.7 kiloohms-centimeters, respectively. It was concluded that the pumice concrete had a higher resistance to chloride ion-penetration. The tests showed that the total charge that passed through the pumice concrete was between 15 and 25% of the Portland cement.

The ultrafine pumice was also proven to significantly reduce the ASR reactivity of concrete and the sulfate-resistance of concrete (Ramasamy et al., 2017). Any reduction in CH content was found to decrease by 40% for a cement replacement of 15% with ultrafine pumice (Ramasamy, 2014).

2.2.4 Waste Glass Powder in Concrete

In the 1960s and 70s, the United States took a more serious approach to recycling. This is due to an effort to reduce landfill sizes. Over the past 50 to 60 years, recycling has become part of the United States economy. Waste glass can be recycled, sorted, washed, crushed, and sieved into rocks, cullet, and powders. Since glass consists mostly of amorphous SiO_2, it is logical that at smaller particle sizes glass should be pozzolanic.

A local glass recycling plant in Utah is Momentum Recycling. They produce roughly 1,000 tons of waste glass cullet a year. Cullet is the size of a fine aggregate particle, typically 0.2 to 0.4 inches (5-10 mm), or roughly 1000 times larger than a typical cement particle. At this size, glass is not pozzolanic. Instead of the cullet, the dust collected from the factory's air filtration system was utilized. An image of the sample can be seen in Figure 2.1 (Lair, 2020). The collection system contains particles smaller than 8 mils (210 micrometers), still 20x larger than an ordinary cement particle. A similar sample of waste glass dust collected from the air filtration system at Momentum, used for another research project found 90% of the particles to be less than 10 mils (274 micrometers), 0.9 to 1.5 mils (23-39 micrometers) on average, and less than 10% smaller than 0.04 mils (1 micrometer) (Bordelon and Choletti, 2020). These particles are generally larger than ordinary cement particles. The exact particle size of the glass used in this study is not known but estimated to be a nominal maximum size of 10 mils (250 micrometers or

#60 sieve). The exact chemical composition of the glass at Momentum is also unknown, but a similar representation can also be found in Appendix A.

Figure 2.1 Waste Glass Powder Sample Collected from Momentum Recycling's Air Filtration System.

Two universities in Bangladesh studied the effects of waste glass (WG) powder on concrete. They determined that glass reacts with cement like a pozzolan. In the study, Portland cement was replaced with WG in increments of 5% up to 25%. The study determined that WG lowered the early strength of concrete. However, by 90 days of curing, the samples containing 10-20% WG achieved a higher strength than the control. It was also determined that the WG increased the flow of the paste and workability of the concrete (Sadiqul Islam et al., 2016). Waste glass powder as a replacement of cement is also shown in tests to reduce ASR expansion but only at replacement values of 30 to 40% (Bordelon and Cholletti, 2021; Fanijo, 2019). Any reduction in CH content has been predicted to be associated with the lower amount of cement that the glass powder replaces. A research study has shown that glass powder used in concrete reduces chloride diffusion more than fly ash type C or F (Tariq et al., 2020).

2.3 Methodology and Procedures

Standards, procedures, and any variance in standards that were used to create the concrete mix design and cylinders are included in this section. Silica fume's small particle size and large surface area decreases concrete's workability and makes it hard to pour and finish. For that reason, initial trial batches were created until a mixture like that reportedly used at the airport parking garage was obtained. Mixing techniques were adjusted in the lab to overcome workability and clumping issues. All concrete-making materials are listed in Table 2.1. The details on the cementitious materials, all the SCMs and the cement, can be found in Appendix A.

Table 2.1 List of Materials and Manufacturers Used in the Study

SCM Symbol	Material	Brand and Manufacturer
SF1	Silica Fume	R.E.D. Industrial Products out of Pennsylvania
SF2	Silica Fume	Eucon MSA Euclid Chemicals
SF3	Silica Fume	Force 10000D GCP Applied Technologies
FA1	Class F Fly Ash	Boral Resources out of Delta, Utah
FA2	Class F Fly Ash	Boral Resources out of Prairie States; Marissa, Illinois
PU	Ultrafine Pumice	Hess Pumice out of Malad City, Idaho
WG	Waste Glass Dust	Momentum Glass Recycling out of Salt Lake City, Utah
	Type II-V Cement	LafargeHolcim out of Morgan, Utah
	Coarse Aggregate	¾" Limestone Aggregate Geneva Rock out of Draper, Utah
	Fine Aggregate	Natural Sand Geneva Rock out of Draper, Utah
	Air Entraining Admixture	Daravair 1000 GCP Applied Technologies
	Water-Reducing Admixture	ADVA Cast 575 GCP Applied Technologies

The exact admixtures used in the parking garage are unknown. However, it is known that Geneva Rock did not use ADVA Cast 575 because it is a third-generation water-reducer, invented after the garage was built. In the first trial, a first-generation lignosulfonate water-reducer, WRDA 64 was used. This water-reducer has been around since before the parking garage was built. Ultimately, the ADVA Cast 575 was selected for this project because it was readily available in the laboratory and as a polycarboxylate-based admixture, it is currently one of the best water-reducers in the industry.

2.3.1 Aggregate Properties

The fine, intermediate, and coarse aggregates were obtained from Geneva Rock in August 2019. Additional fine and coarse aggregates were collected in August 2020 and again in March of 2021. The gradations, specific gravities, and absorption capacities of the aggregates were measured by the students at UVU using the standards found in Table 2.2.

Table 2.2 Standards Followed to Find Aggregate Properties

Standard	Purpose
ASTM C127	Specific Gravity and Absorption Capacity of Coarse Aggregate
ASTM C128	Specific Gravity and Absorption Capacity of Fine Aggregate
ASTM C136	Sieve Analysis and Gradation of Aggregates

Sieve analysis readings can be found in Appendix B. The average gradations of fine, intermediate, and coarse aggregates are shown in Figure 2.2, based on the sieve analyses. The average oven-dried specific gravities of the fine, intermediate, and coarse aggregates were 2.53, 2.44, and 2.54, respectively. The absorption capacities were determined by 2020 to be 1.0%, 3.2%, and 1.8%, respectively. Upon a second measurement completed in the summer of 2021, the absorption capacity was remeasured and corrected for the fine and coarse aggregate to be 1.6% and 2.0% (both slightly higher). This adjustment made a difference in slightly higher batch weights on SF1b, SF2, and SF3 mixtures.

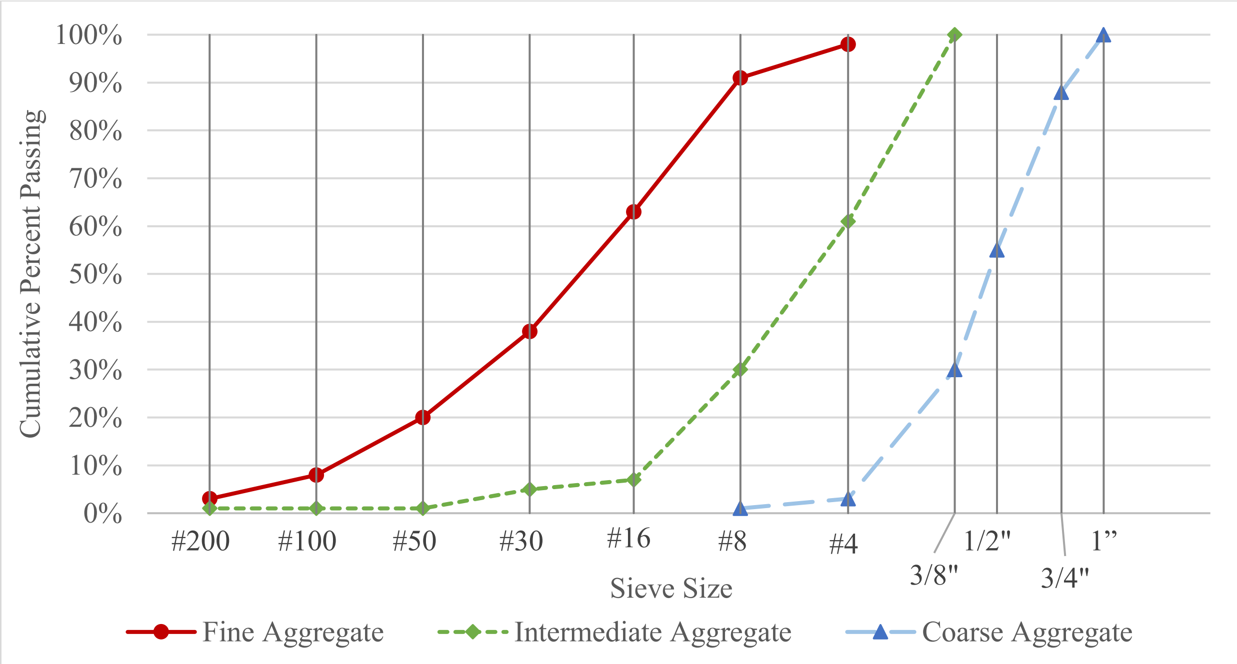


Figure 2.2 Gradation Curves for the Natural Sand Fine Aggregate, Limestone Intermediate Aggregate, and Limestone Coarse Aggregate.

2.4 Concrete Mix Design

Trial batches were attempted aiming to recreate the mix design and properties reported for the SLC airport parking garage from 1989. Since the material suppliers are slightly different, it was expected that a replica was not likely to be on the first trial. Adjustments ended up being made to the aggregate blending and the w/cm ratio based on what was noted from the 1989 design.

2.4.1 Aggregate Blend

Anecdotally, the airport mix was believed to contain three sizes: fine, intermediate, and coarse-sized aggregates. Since the aggregates utilized in this study were different than those of the 1989 airport parking garage, the trail batches were first created to determine a blend of aggregates for this study that would produce good workability. The trial mixture designs and respective fresh property measurements can be found in Appendix C.

The aggregate gradation and volume have a major impact on concrete workability. After the first trials, a blend of 60% coarse aggregate and 40% fine aggregate was selected (batches 3 and 5 through 14). This met the Tarantula Curve, as seen in Figure 2.3, which defines limits to the blended percent retained on each sieve to improve concrete workability. This also meant that no intermediate aggregate was used or needed to have a good workability.

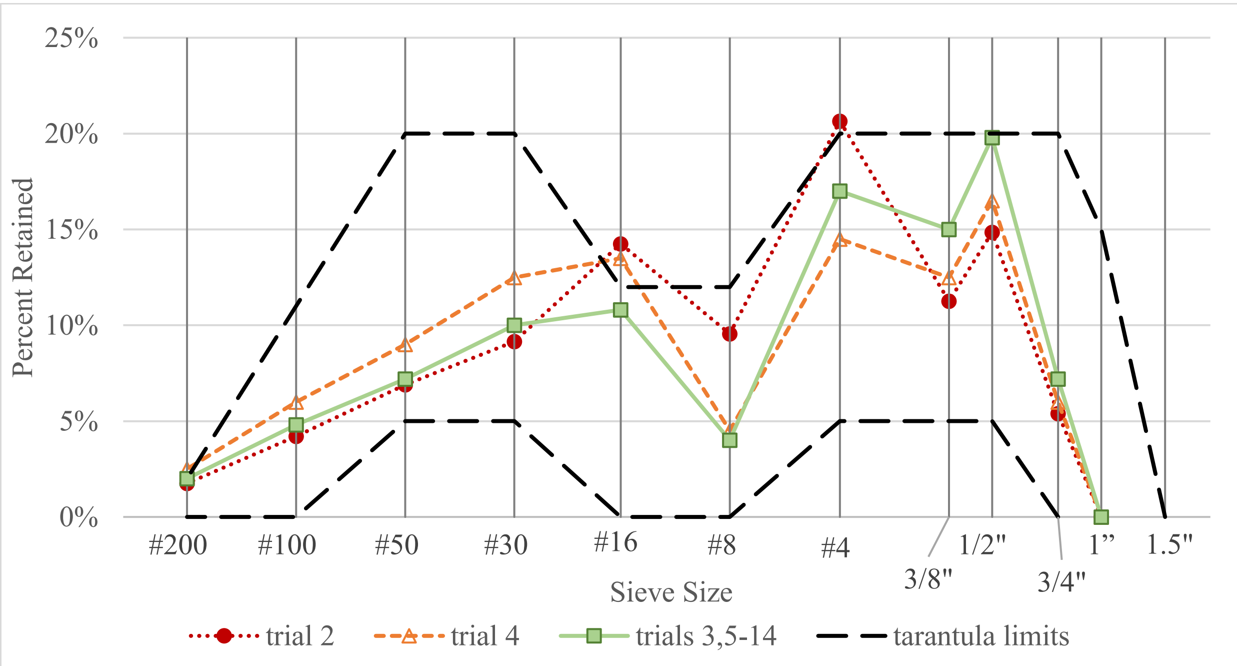


Figure 2.3 Tarantula Curve for the Coarse and Fine Aggregate Blend Used in the Trials.

2.5 Concrete Mix Proportions

The w/cm ratio for the airport parking garage was reported as 0.38. This is a very low w/cm ratio compared to what UDOT bridge decks typically are, but for the purpose of this study to first match the mixture that was used at the airport parking garage, a w/cm of 0.38 was created.

To reduce the amount of total cementitious content for economic reasons and to minimize deck shrinkage that might result, the amount of aggregate was aimed to be high. Initial trials contained roughly 74% total aggregate to concrete volume. These mixtures were too unworkable, dry, and/or honeycombed. Specific calculated aggregate volumes and workability of these initial trials are shown in Appendix C. The amount of aggregate volume was reduced to about 68% for the final mixtures used in this study.

All aggregates were oven-dried for at least eight hours before adding to a mix. The aggregates were also batched at this dry condition. Additional water was calculated based on the absorption capacity of each aggregate and the weight of that aggregate, then added as additional weight to the total batch water measured. Actual batched amounts (in oven-dried aggregate condition) are listed in Appendix D. The calculated saturated-surface dry condition proportions and assuming no entrapped air is shown in Table 2.3.

Admixture dosages were taken from manufacturer recommendations. The air-entrainer dosage was 3 fl.oz. per 100-lbs of cementitious (maximum dosage recommended). The water-reducer dosage for most of the trials was 5 fl.oz. per 100-lb of cementitious. The manufacturer of the water-reducer recommends a range from 3 to 6 fl.oz. per 100-lb cementitious material. Mixture SF1b, SF2 and SF3 were created using 20% more water-reducer dosage, at 6 fl.oz. per 100-lbs of cementitious to further improve workability of these silica fume mixtures. Note that SF1a and SF1b are the same actual batch amounts (see Appendix D) except for the different water-reducer dosage.

Table 2.3 Concrete Mixture Proportions Scaled up to Cubic Yards and at Saturated Surface Dry Condition

Mixture		CON	SF1a	SF1b	SF2	SF3	FA1	FA2	PU	WG
Trial #		6	9	12	13	14	7	8	10	11
Cement	lbs	751	679	681	679	679	632	630	631	629
Silica Fume #1	lbs		66	66						
Silica Fume #2	lbs				67					
Silica Fume #3	lbs					66				
Fly Ash #1	lbs						112			
Fly Ash #2	lbs							112		
Ultrafine Pumice	lbs								112	
Waste Glass Powder	lbs									112
Coarse Aggregate	lbs	1766	1751	1756	1755	1754	1751	1748	1745	1750
Fine Aggregate	lbs	1165	1158	1166	1164	1164	1135	1156	1154	1158
Water	lbs	287	290	284	283	284	291	290	290	290
Water-Reducer	fl. oz.	38	37	45	45	45	37	37	37	37
Air-Entrainer	fl. oz.	23	22	22	22	22	22	22	22	22
w/cm ratio	-	0.38	0.39	0.38	0.38	0.38	0.39	0.39	0.39	0.39
percent pozzolan	-	0%	9%	9%	9%	9%	15%	15%	15%	15%
percent agg/concrete volume	-	69%	68%	68%	68%	68%	68%	68%	68%	68%

2.6 Mixing Process and Fresh Property Tests

Silica fume needs to be dispersed evenly to maximize its concrete enhancing properties. The ASTM C192 standard does not give enough mixing time for the silica fume to disperse evenly. This creates a clumpy mixture. The Silica Fume Association published a manual on how to fix this problem (Holland, 2005). The manual recommends mixing 75% of the water with the coarse aggregate then adding the silica fume to coat it. Most concrete cracking occurs at the interfacial transition zone or where the cement pastes stick to the coarse aggregate. It makes sense that coating this weak spot with the silica fume would enhance the overall properties of the concrete (Holland, 2005).

Different mixing procedures were tried that included steps and suggestions from both the standard and the Silica Fume User's Manual. Before any ingredients were added, the drum was wet down. On each batch, air-entrainment and water-reducer were added with the batched water. For mixtures batched with any of the silica fume SCMs, the silica powder was mixed with roughly 50% of the batch water in a bucket on the side to create a slurry. For all batches, all the coarse aggregate was added to the drum and roughly 25% of the batch water was added, then mixed for one minute. For the silica fume mixtures, the silica slurry was added to the drum with the damp coarse aggregate and mixed for an additional minute. On all batches, the sand, cement, any other SCMs, and the remaining 25% of the batch water was added to the mixture, then mixed for four minutes. A rest period of three minutes and another five minutes of mixing followed prior to fresh property testing.

Mixture temperatures were also measured using a digital thermometer in the fresh concrete. Slump, unit weight, and pressurized air measurements were made of trials and final batches. All standards followed can be found in Table 2.4. The same person measured the fresh properties on each trial to eliminate variance.

Table 2.4 Standards Used to Mix and Measure Fresh Properties of Concrete

Standard	Purpose
ASTM C31	Making and Curing Concrete Specimens
ASTM C143	Measuring Slump of Fresh Concrete
ASTM C138	Measuring the Unit Weight of Fresh Concrete
ASTM C192	Making Concrete in the Lab
ASTM C231	Measuring the Air Content of Fresh Concrete

A minimum of eight 4x8 cylinders were created of each final mixture. These were rodded using 3/8" rods 25 times per lift, plus tapped on the sides 12 times per lift, for 2 lifts, following the ASTM C31 standard. Samples were demolded roughly 24 hours after casting and placed into a water bath with a controlled constant temperature of 72 °F.

2.7 Concrete Hardened Tests

The standards used to measure the hardened properties of concrete are listed in Table 2.5. Six cylinders from each trial were evaluated for the concrete's compressive strength; three for the 7-day strength, and three for the 28-day strength. Cylinders were compressed approximately 20 to 30 minutes after removing from the curing tank, with neoprene endcaps on a compressive load frame at UVU following the loading rate for a 4x8 cylinder.

The remaining two cylinders were kept in the curing bath for one year before removing and delivering to the laboratory at BYU for rapid chloride testing. Samples were cut into pucks that are 2" in length, painted on the sides with epoxy to prevent leakage during the test, placed in a vacuum chamber for 3 hours, then saturated prior to placing in the testing device. The testing chamber has 0.3N NaOH on the positive end, 3% NaCl on the other negative end with 60 volts applied for six hours. Electrical resistance was measured through the sample in coulombs. The airport parking garage was designed to have low permeability, which corresponds to 2000 coulombs or less.

Table 2.5 Standards Used to Measure the Hardened Properties of Concrete

Standard	Purpose
ASTM C39	Compressive Strength Test of Concrete
ASTM C1202	Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

2.8 Summary

Overall, different SCMs were studied at different dosage rates. However, the basic mixture was kept the same, with the same w/c ratio of 0.39, same admixture types, same aggregate blends and amounts. Water-reducer and air-entrainer were used in all mixtures. The mixing procedure for the silica fume concrete batches was modified from the control based on recommendations from the Silica Fume User's Manual (Holland, 2005) because the very small particle size of the powder might create clumping issues with normal mixing procedures. Water-reducer amount was also studied with one silica fume type. Fresh properties, strength, and chloride resistance were measured as described in the next section.

3.0 LAB RESULTS

3.1 Overview

This section includes the measured mixture properties. This includes the fresh properties of slump, unit weight, and air content, the hardened compressive strength measurements, and the results from the rapid chloride permeability tests. Only the results from trials 6-14 are included in this section since these were after the initial mixture workability issues were resolved and consist of only one type of SCM in each mixture. Results measured from any of the initial trials 1-5 can be found in Appendix C.

3.2 Fresh Properties

The fresh properties of each final mixture are listed in Table 3.1. The slump target was taken to be the recommended slump for a slab which is between 1-3 inches (Mehta & Monteiro, 2014). The recommended slump was only met with the control mixture with the addition of a water-reducer. This same water-reducer amount was used on each SCM mixture to avoid the dosage of admixture as a variable. The silica fume SF1a had very low slumps of ¼ in. and was very unworkable. The increase in water-reducer by 20% added to the remaining silica fume batches did improve the workability, as expected. The low slump silica fume mixture exhibited honeycombing (see Figure 3.1). The honeycombing may have affected the concrete's strength. For the mixtures with fly ash and waste glass, the slump was so high they appeared soupy and there was no honeycombing. The mixtures with either type of fly ash or waste glass had too high of a slump and did not need the addition of a water-reducer. Future mixtures that use fly ash or waste glass are thus recommended to be created omitting or with less water-reducer.

The target air content of 7% +/- 1% was not met by most mixtures. The maximum recommended dosage for an air-entrainer from the supplier was used. In future trials, a greater dosage going above the maximum recommended may be used.

Table 3.1 Fresh Properties and Observations of Each SCM Mixture

	Control	SF1a	SF1b	SF2	SF3	FA1	FA2	PU	WG
Mixing Notes		closest to airport mix design	a bit more WR used	a bit more WR used	a bit more WR used				
Slump	1 ½"	¼"	1 ¼"	1 ½"	1 ½"	8 ½"	8 ½"	¾"	8 ½"
Temperature	84 °F	83 °F	74 °F	71 °F	73 °F	71 °F	82 °F	76 °F	71 °F
Unit Weight	149 pcf	147 pcf	145 pcf	142 pcf	142 pcf	147 pcf	146 pcf	148 pcf	146 pcf
Air Content	2.1 %	3.15 %	3.5 %	6 %	5.5 %	2.3 %	3.2 %	2.5 %	3.2 %
Workability Notes	very workable and wet	stiff	a bit more workable than SF1a, texture of cookie dough	a bit more workable than SF1a, texture of cookie dough	a bit more workable than SF1a, texture of cookie dough	very workable, more than control. Like rice pudding	seemed more liquid than FA1	between fly ash and SF workability	soup, moves like soup
Finishing Notes	finished well	finished well	finished well	finished well	finished well	finished well but soupy	finished well but soupy	finished well	very soupy and wet

3.3 Hardened Properties

Figure 3.1 shows the best and worst looking cylinders from trial 9 (Silica Fume 1 with the original lower water-reducer amount) after being demolded. The control batch with no SCMs, had locations exhibiting honeycombing. Additional photos of the broken cylinders at 7- and 28-day compressive strengths for each mixture can be found in Appendix E.

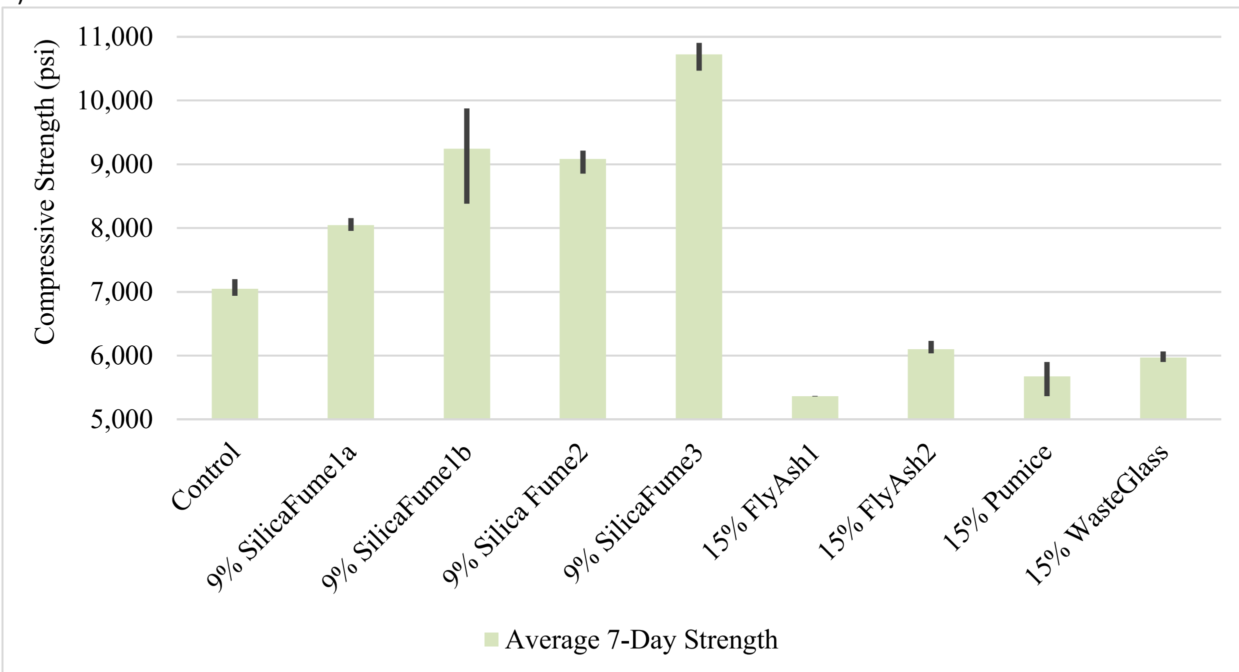
Figure 3.1 Worst (Left) and Best (Right) Compacted Cylinders Made from SF1a.

Compressive strength results can be seen tabulated in Table 3.2 or graphically in Figure 3.2 and 3.3. Three cylinders were evaluated for each age and each mixture. All the mixtures containing 9% silica fume, had the highest 7- and 28-day strengths of 10,724psi and 10,558psi, respectively. With the addition of water-reducer to SF1b, SF2, and SF3, these mixtures achieved at least 9000psi strength as early as 7 days. The SF3, which was from GCP Applied Technologies, produced the highest strength in this study. In comparing the different class F fly ash sources, one source FA2 from Prairie States, gave slightly higher strengths in this study. All SCMs except the silica fume, so the fly ashes, pumice and waste glass, all had similar or slightly lower strengths than the control without any SCM. An early trial, #5 which contained 15% fly ash and 7.4% silica fume (which was the SCM blending from the original proposed airport parking garage structure), achieved the lowest 7-day strengths of 5,363psi (see Appendix C for results from other trials).

Table 3.2 Compressive Strengths of Each SCM Mixture

	Control	SF1a	SF1b	SF2	SF3	FA1	FA2	PU	WG
7-day psi	7008	7958	9472	9179	10470	5357	6229	5362	5946
7-day psi	6937	8156	9875	8852	10905	forgot to tare	6035	5752	6066
7-day psi	7197	8023	8380	9217	10797	5369	6033	5900	5897
Average 7day	**7047**	**8046**	**9242**	**9083**	**10724**	**5363**	**6099**	**5671**	**5970**
Standard Deviation	134	101	774	201	227	8	113	278	87
Coefficient of Variation	2%	1%	8%	2%	2%	0%	2%	5%	1%
28-day psi	8681	10127	9316	9409	10746	6455	8407	6556	6986
28-day psi	8219	8865	9336	9971	10219	6575	8043	7343	7071
28-day psi	7836	9776	9163	9286	10710	6816	7658	6733	7151
Average 28day	**8245**	**9589**	**9272**	**9555**	**10558**	**6615**	**8036**	**6877**	**7069**
Standard Deviation	423	651	95	365	294	184	375	413	83
Coefficient of Variation	5%	7%	1%	4%	3%	3%	5%	6%	1%

a)



b)

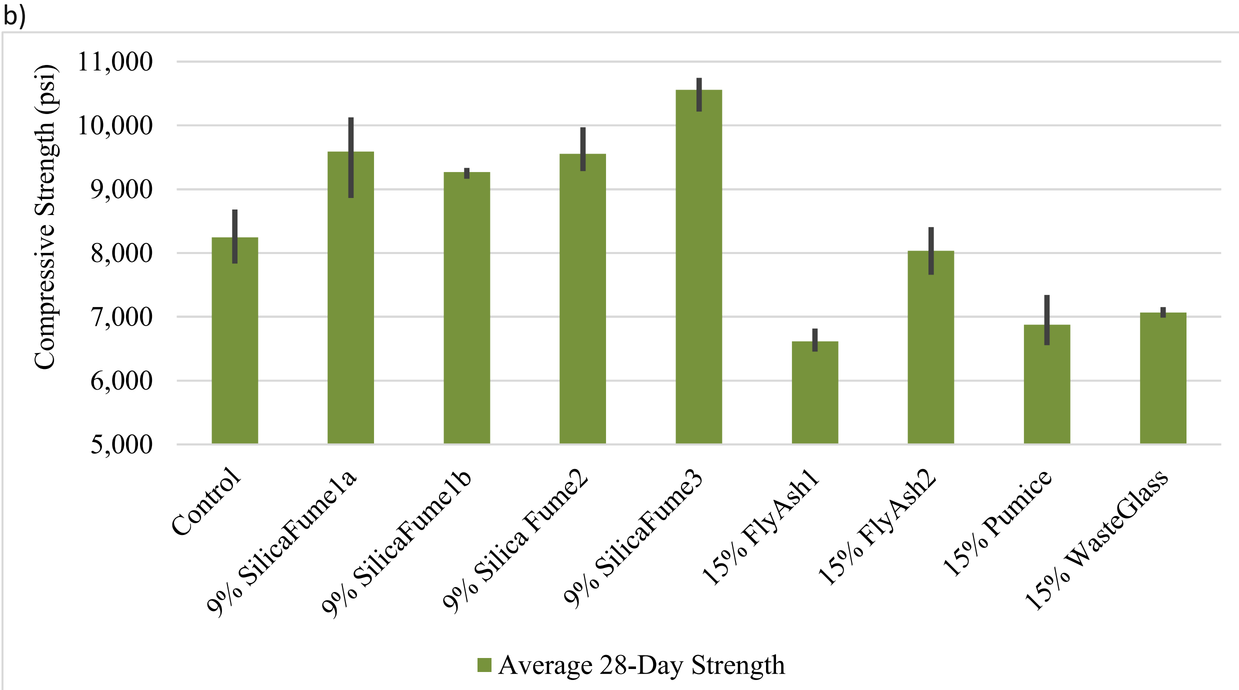


Figure 3.2 Average, Maximum, and Minimum Compressive Strengths of Three Cylinders for Each Mixture Tested at a) 7 and b) 28 Days of Age.

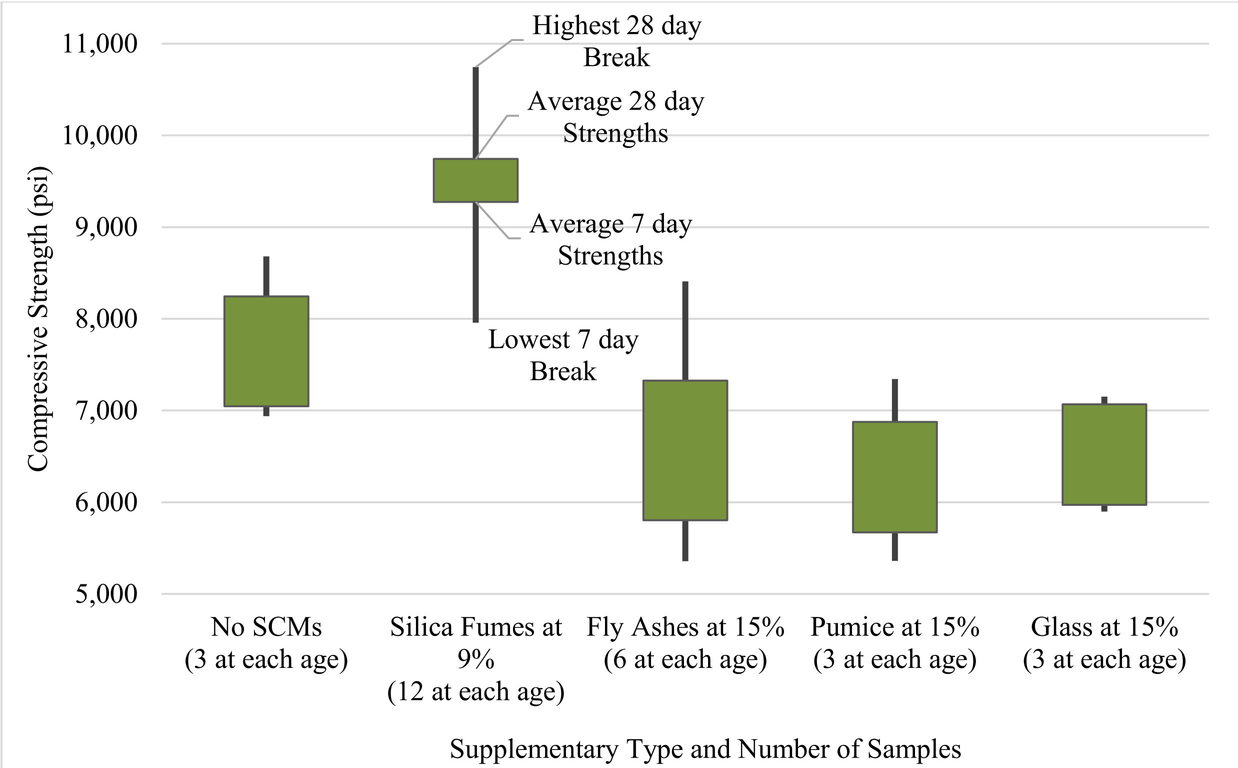


Figure 3.3 Summary of the Different Types of SCMs Versus Strength.

3.4 Chloride Results

A cylindrical specimen of each mixture was cut into two 2” long pucks and evaluated for magnitude of chloride resistance based on the ASTM C1202 test, measured by the students at BYU. Samples were over one year in age when the rapid chloride measurements were performed.

Results are shown graphically in Figures 3.4 and 3.5 and numerically in Table 3.3. The control mixture containing no SCMs had “low” chloride penetration levels. The addition of all 9% silica fume or 15% of fly ash 1 mixtures improved the chloride resistance to the “very low” level. Unfortunately, the addition of 15% pumice or 15% waste glass either had no significant change or had worse chloride penetration levels than the control. The mixture with fly ash 2 at 15% was lower than the control but classified as “low” chloride resistance instead of the very low level of its counterpart fly ash product.

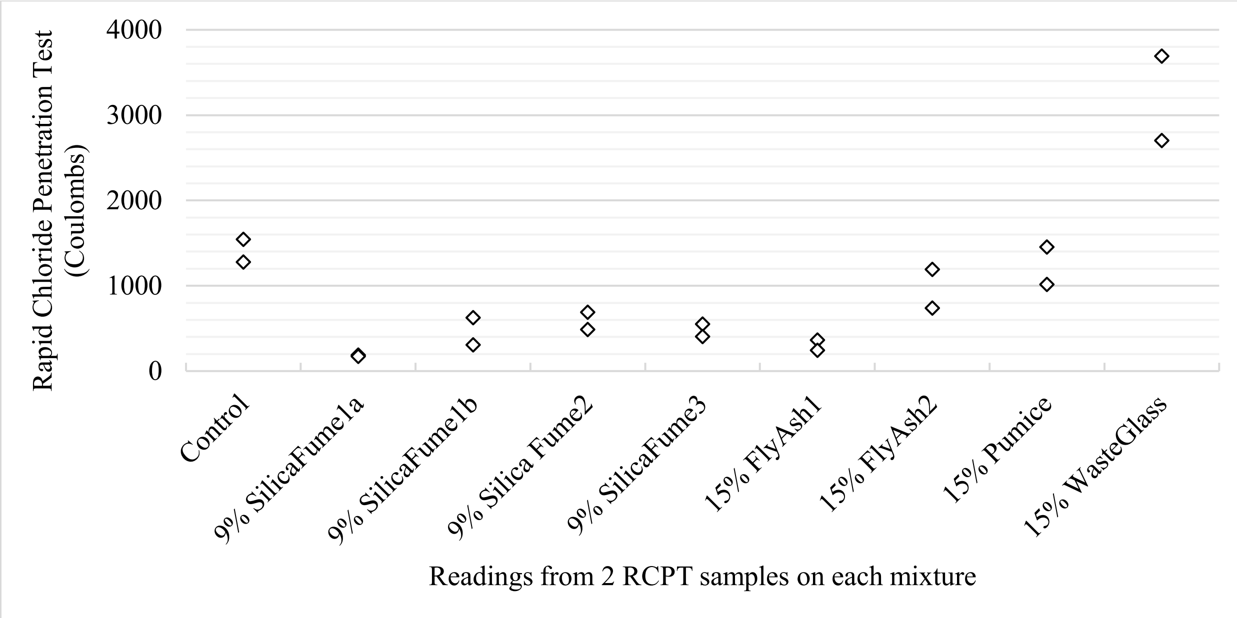


Figure 3.4 Rapid Chloride Test Readings of Each Sample.

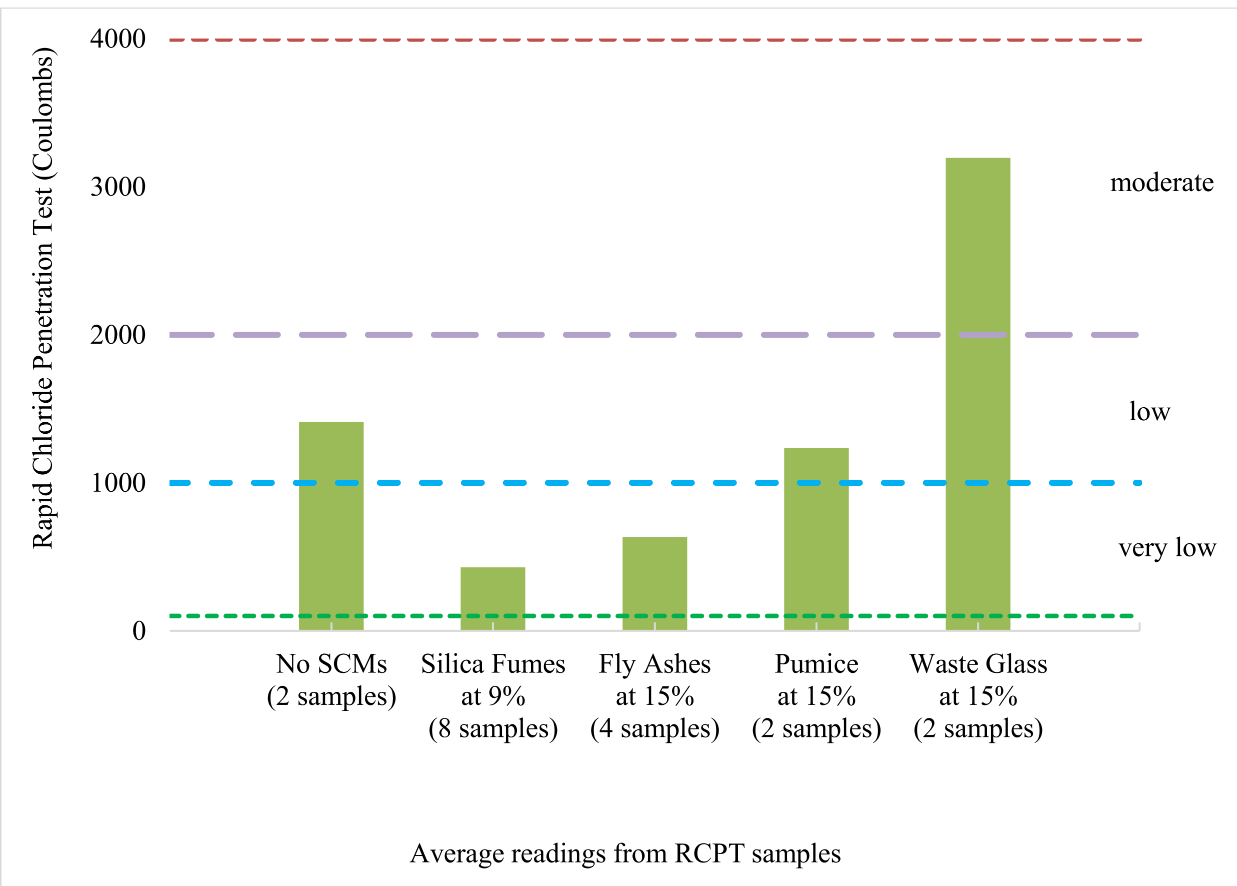


Figure 3.5 Average Rapid Chloride Test Readings of Each SCM.

Table 3.3 Results from the Chloride Ion Penetration for Each Sample

	Individual readings on the RCPT Samples (Coulombs)		Average RCPT Value (Coulombs)	ASTM C1220 Chloride Penetration Level	Average Absorption (% wt. increase) during RCPT
Control	1544	1278	1411	Low	1.62%
9% SilicaFume1a	174	188	181	Very Low	1.05%
9% SilicaFume1b	625	309	467	Very Low	3.19%
9% Silica Fume2	689	489	589	Very Low	3.10%
9% SilicaFume3	404	552	478	Very Low	2.02%
15% FlyAsh1	245	362	303.5	Very Low	3.53%
15% FlyAsh2	740	1190	1283	Low	2.66%
15% Pumice	1454	1017	1545	Low	3.18%
15% WasteGlass	2701	3690	3895	Moderate (worse than control)	4.40%

Sample weights were also recorded before and after this test to find if the samples absorbed the liquid solution during the RCPT. The average of two absorption calculations is shown in Table 3.3 with specific absorption measurements plotted against the RCPT reading for the same sample in Figure 3.6. There was not enough data to statistically draw any conclusions at this time on whether the amount of solution that is absorbed is correlated with the RCPT reading.

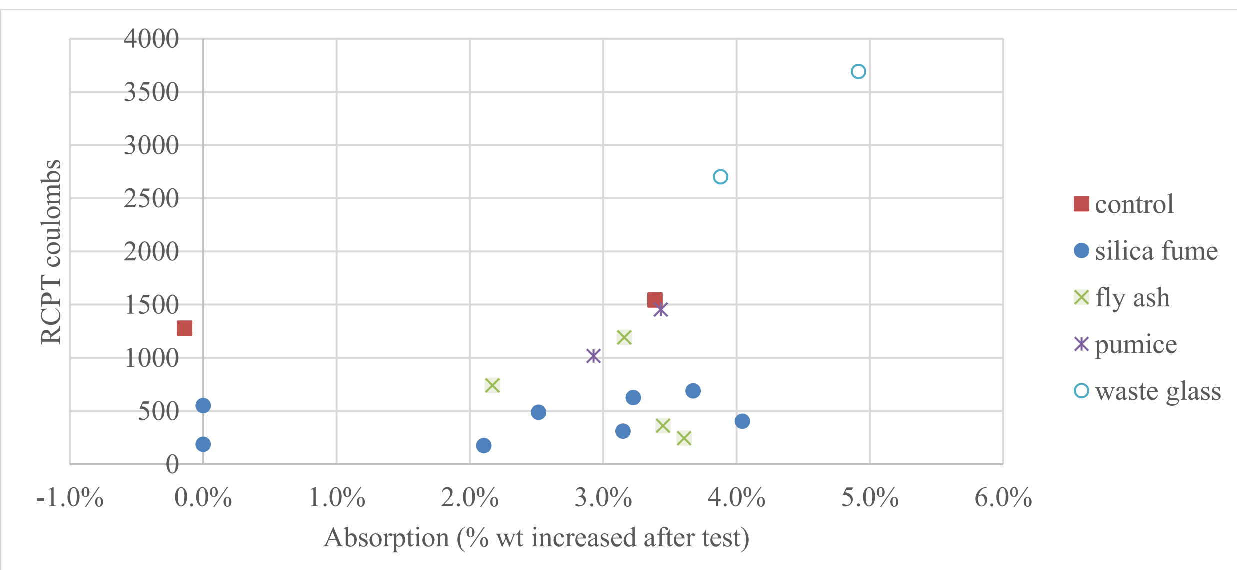


Figure 3.6 Rapid Chloride Test Readings of Each Mixture.

3.5 Summary

The key test parameter of this research report is chloride resistance. All the silica fume types at 9% replacement of cement and one of the fly ash types at 15% replacement of cement brought the chloride penetration level to “very low.” The pumice did not make a significant difference on the chloride penetration, and the waste glass dust used here exhibited higher chloride penetration levels than the control.

Testing results also verified that the concretes with 9% silica fume had significantly higher 7- and 28-day strengths. The other SCMs, fly ash, pumice, and glass at 15% replacement rate all decreased strengths. The workability of silica fume was significantly stiffer, until more water-reducer was added, and then the slump was similar to the control. Fly ash and waste glass mixtures were significantly higher slumps even without additional water-reducer.

4.0 DISCUSSION

4.1 Overview

This section provides insight for discussion comparing the different SCMs studied in terms of the impact on concrete mixture adjustments needed, cost of transporting and using the SCM, workability considerations, and environmental impacts known to be associated with that SCM. The comparison was done as part of a requirement for the capstone class at UVU. Impacts of each SCM are important to consider. The impact categories and a summary table of information (Table 4.1) are included in this section. The categories compare the different SCMs discussed in this report. The values used for average compressive strengths, slump, and chloride permeability are taken from this study.

4.2 Public Health, Safety, and Welfare

Public health and safety are of the utmost importance in any construction project. The safety includes not only the public, but also any workers involved in a project. The safety concerns discussed are associated with crystalline silica inhalation associated with a specific SCM.

Crystalline silica is considered a carcinogen. If too much is inhaled, it can cause major health problems including silicosis. Most people with silicosis worked in handling products containing crystalline silica. However, between 2001 and 2010 around 1,437 people died from it in the United States. Of those people, 28% of them ranged between 15–44 years old (Bang et al., 2015). Many supplementary cementitious materials are beneficial because they contain silica. The amorphous form of silica, such as is found in pumice and in silica fume, are verified to be non-crystalline. Class F fly ash samples have been evaluated by Chancey et al. and found to be about 16.4% based on X-ray Diffraction Analysis or 17.7% based on Multi-Spectral Image Analysis (2010). Waste glass is also found to have 70% or more amorphous silica (Mallum et al., 2021). Medical studies have shown no connection from the amorphous form of silica to health problems in humans (Merget et al., 2002; Krug, 2022). Aggregate particles are the main source of crystalline silica found in concrete when batching or cutting.

Table 4.1 Impact Comparison of Supplementing Cementitious Materials

Category	Subcategory	Cement or Supplementary Cementitious Material					
		Portland cement	**Silica Fume**	**Prairie States Fly Ash**	**Delta Fly Ash**	**Pumice**	**Waste Glass Powder**
Public Safety	Contains Crystalline Silica?	No	No	16 – 18%	16 – 18%	No	< 30%
Cost	Material Cost per yd^3 of Concrete in 2021 dollars	$164	$164 + $1/lb Silica Fume + $8 Water-Reducer	$164 + $0/lb Fly Ash	$164 + $0/lb Fly Ash	$164 + $0.11/lb Pumice	$164 + $0.06/lb Waste Glass Powder
	Local to Utah?	Yes	No	No	Yes	Yes	Yes, only 1000 tons/yr
	Recommended Percentage of Replacement	-	5-10	15-50	15-50	15-25	10-20
Mechanical Properties	Average 28-day Compressive Strength at Recommended Percentage	8,245	9,589	8,038	6,615	6,877	7,069
	Slump (inches)	1 1/2	¼	8 1/2	8 ½	3/4	8 1/2
	Lowers Chloride Permeability?	-	Yes	Yes	Yes	Maybe	No
	Mitigates Alkali Silica Reaction?	-	Maybe	Yes	Yes	Yes	Yes
Environmental Impact	lb of CO_2 Emissions per US ton of cement or SCM product	1,918	28	186	186	NA	15
	Life Cycle (% of life increase per 1% substitution of cement)	0%	18.0%	3.8%	3.8%	NA	7.6 – 13.0%
	By-Product or Manufactured?	Manufactured	By-Product	By-Product	By-Product	Excavated	By-Product
Global and Economic Impact	Global Market in 2023	$427B	$470M	$6.14B	$6.14B	NA	$1.31B
	Global Market Projection	$987B by 2032	$760M by 2032	$9.85B by 2032	$9.85B by 2032	NA	$2.26B by 2030

*NA = Information Not Available

4.3 Cost

Cost is often the most decisive factor in any concrete project. Factors that affect cost include the price of material, transportation/shipping, any extra labor or equipment associated with mixing, pouring, finishing, curing, any additional maintenance costs, or end-of-life disposal costs. The costs shown in this Table 4.1 are mainly based on market mixture material costs only.

The prices for the Portland cement, silica fume, and fly ash were provided by Geneva Rock (Smith, 2021). The mix designs shown in this report with 9% silica fume replacement equate to a concrete mixture at $244 per cubic yard. Silica fume concrete, which greatly increases concrete's strength, is almost unworkable. If silica fume is selected to be used on Utah bridge decks, the workability challenges will need to be addressed and possibly run through the higher water-reducer dosage at added cost.

The fly ash SCMs are estimated to not cost extra to the basic mix design. The price obtained from Hess Pumice was $220 per ton, or $0.11 per pound, which is higher than Portland cement, fly ash, and waste glass (Jeppsen, 2021).

The two SMC types not available near Utah are all the silica fumes and the Prairie States fly ash. A further increase in the cost of shipping would need to be accounted for because of the transportation/shipping of these SCMs for Utah projects. Future production availability or changes in production quality of each SCM are also factors that may need to be considered. Coal-burning power plants are closing around the United States due to the zero-emissions goal of the federal and some state governments. The National Precast Concrete Association (2017) indicates that fly ash is dwindling and outdated. However, in the same article, the American Coal Ash Association estimates fly ash production will increase by 2.6% through 2033.

Since Momentum Recycling does not crush waste glass beyond a cullet size into a powder, the price shown in Table 4.1 is a low estimate. It would cost extra to grind the glass before using it in concrete. Momentum Recycling collects about 13,000 tons annually of glass (Meehan, 2017) and measures about 1000 tons of waste glass powder produced per year (Lair, 2020). The cost per ton for this current waste glass powder is between $75-$125 (Lair, 2020), which is similar to the cost of Portland cement.

4.4 Social and Cultural Impact

Social and cultural impacts depend on some other factors. Northern Utah, where most of Utah's population lives, has significant air pollution. Since the region is mountainous, air pollution gets trapped and does not quickly disperse. Less carbon and particulate emissions by manufactured materials will create a better social stigma. Similarly, faster and cleaner construction is preferred by the population located near or using the roadway or bridge under construction. Any time roads or lanes are closed for construction, traffic is increased. Increased traffic causes more idling cars and more air pollution. It also causes more accidents. The Federal Highway Administration estimates that one fatality occurs for every $112 million spent on roadway construction (2021).

If silica fume or other SCMs can increase road strength, it may allow for reduced construction closure times. The higher durability of the SCM mixtures also decreases the frequency for any road maintenance. Decreased construction delays would decrease road fatalities, traffic, and air pollution. This would enhance the general social and cultural well-being of Utah.

4.5 Environmental Impact

Environmental factors are becoming more of a priority for many construction projects, especially with the political atmosphere of today. It is the goal of the federal and some state governments to reduce or eliminate carbon emissions. This is true in the United States and around the world.

The production of Portland cement accounts for 6-8% of the world's carbon emissions (Malhotra and Holland, 2022). Replacing cement with an SCM is a current trend for reducing carbon emissions. Silica fume, fly ash, and waste glass are by-products or recycled materials. These may contribute to carbon emissions from the manufacturing and heating processes, but because their uses as an SCM are not the original purpose for the manufacturing of these products, they have some environmental benefits by reducing landfill waste. Pumice is a virgin material taken from the Earth through excavating and sieving, so the carbon footprint is lower than other SCMs that require more heat to create.

The life cycle is important in sustainability practices. Most concrete is designed to last roughly 50 years if maintained. The SLC airport parking garage had a design life of 75 years. Silica fume drastically increases the life cycle of concrete so far. Since its use in large-scale projects began in the 1980s, it is hard to know for sure how long the life cycle will be. The CO_2 emissions and estimated service life (using Life365 software) for Portland cement, class F fly ash, and silica fume reported in Table 4.1 are from Norchem (2011). Using the same service-life prediction software, Tariq et al. found that waste glass powder at 30% had 2 to 3.5 times the service life of that of fly ash with the same content 30% (2020). The CO_2 emissions related to just processing container glass are roughly 80 kg of CO2 for every ton of glass processed (Zier et al., 2021). If only 1000 of the 13,000 tons are made as potential powder for cement, this comes to about 14.9 lbs of CO_2 for every ton.

4.6 Economic and Global Impact

The global impacts depend on environmental factors. Local, regional, and global environments are affected by carbon emissions. The carbon emissions for each SCM are given in Table 4.1. The global impact also depends on economic factors. Concrete and cement production are high-grossing industries in the hundreds of billions of US dollars (Global Market Statistics, 2024a). Each SCM stimulates local, national, and global economies. All SCMs produced near Utah will impact Utah's economy. Economic market projects indicate that the pozzolan industry (including fly ash, silica fume, and natural pozzolans like pumice) will go from $72.85B in 2023 to $124B by 2032 (Value Market Research, 2024). The fly ash industry leads production costs in the billions (Expert Market Research, 2024). Silica fume, despite its higher cost compared to cement, is only in the hundreds of millions on the global market (Global Market Statistics, 2024b). Glass production and recycling is also a billion-dollar industry (Virtue Market Research, 2024). The 2023 and future projections of these markets are shown in Table 4.1.

4.7 Availability

This project focused on comparing the effects of different SCMs on concrete. The SCMs in question are silica fume, class F fly ash, pumice, and waste glass powder. All are available in the United States. The silica fumes and the one type of fly ash would have to be shipped to Utah if they were to be used. The waste glass powder is local but has a limited supply and may not be economically feasible.

4.8 Summary

This section reviewed other factors besides mechanical properties that may be associated with selection of using a specific SCM. In general, all are safe to use and handle, with some risk of carcinogenic silicosis from handling the waste glass powder or the fly ash. In terms of cost, the cheapest option today is fly ash and the most expensive is silica fume (not only because of the material but also the added cost needed for including water-reducer to the mixture). For reducing carbon emissions by adding an SCM to cement, all SCMs improved the air quality compared to cement, with silica fume production having the least impact on air quality from its production. For life-cycle analysis, all SCMs were expected to improve the service life of the concrete over plain Portland cement, with silica fume being the most effective at extending the service life.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The purpose of this research study was to investigate the mechanical properties associated with using supplementary cementitious materials for future bridge decks. In particular, the project was inspired by the recently analyzed parking garage structure in Salt Lake City's airport which contained 9% silica fume and was found to have superior chloride resistance and minimal cracking even over 28 years of service life. This study explored three different sources of silica fume, two sources of class F fly ash, a local ultra-fine pumice, and a locally collected waste glass powder. Fresh properties, strengths, and particularly the chloride permeability test were measured for all the mixtures with multiple sample replicates.

5.2 Findings

Most of the SCMs studied were found to reduce the chloride permeability of concrete. Any of the manufactured SCMs (silica fume, fly ash, or pumice) would be beneficial as a replacement of cement for the purpose of providing more chloride ingress resistance. The samples with waste glass powder were found to have higher chloride permeability, worse than the control.

The magnitude of chloride resistance was significantly improved with all the silica fume concrete mixtures compared to the other SCMs studied. One of the class F fly ashes (from Delta, UT) used in concrete was also found to significantly improve the chloride resistance of concrete. The silica fume with the most reduction in chloride permittivity was from R.E.D. Industries in Mississippi.

The silica fume concrete mixtures significantly increased the strength of the concrete. This could benefit construction for earlier openings of bridges to traffic. The silica fume concrete needed to be mixed with more water reducing admixture to ensure enough workability and slump, and to prevent honeycombing. The silica fume that gave the highest compressive strengths at 7 and 28 days was from GCP Applied Technologies.

The fly ashes, the waste glass, and the pumice all were found to have lower strengths compared to the control mixture.

Early trials led to the use of a higher cement paste to aggregate ratio and a high-quality water-reducer for improved workability and decreasing the likelihood of honeycombing.

Literature research on other impacts of these SCMs further emphasizes that the CO_2 emissions would be reduced with any SCM, with silica fume of waste glass powder (collected from the dust after crushing glass to a cullet size) having possibly the lowest emissions.

Fly ash and waste glass powder are currently the cheapest options as an SCM. The fly ashes and the waste glass were found to significantly increase the workability of the concrete, meaning there is no need for a water-reducer, and this would further decrease the cost selecting these as an SCM.

5.3 Limitations and Challenges

The dosage of silica fume was selected to be 9% so that it matched what was implemented in the Salt Lake City Airport Parking Garage structure. The other SCMs were added at a different dosage rate mainly because from previous experience and literature studies, a 9% dosage of those SCMs is not sufficient to see the benefits on properties. The 15% dosage rate was selected since this was part of the original proposed fly ash amount for the same parking garage structure prior to construction. This amount falls within the typical recommended dosage rate for these SCMs. This study did not investigate optimization of the percentage replacement of cement, but that would need to be performed prior to bridge deck construction with any of these SCMs. In addition, the cement industry has switched over to using Type IL cements which contain a higher limestone dust amount than the Type II/V cement used in this study. This may further alter the chloride resistance, strength, and workability of concrete mixtures with or without SCMs.

Since the civil engineering program at UVU is new, some equipment to evaluate and make concrete was not available. In the ASTM standard for mixing concrete, vibration is necessary for low-slump concrete. As no vibrator was available in the lab, the low-slump mixtures (SF1a and PU) were not vibrated. This may have contributed to the copious amounts of honeycombing. The honeycombing may have contributed to a lower compressive strength value.

Higher paste contents may result in greater shrinkage of concrete. The shrinkage was not measured for this study, but the magnitude of shrinkage is recommended to be checked with these mixtures. With w/c ratios around 0.38, as was aimed for in this study, autogenous shrinkage should not be an issue, however, drying shrinkage from the arid climate of Utah may have a greater impact on the higher paste contents. A good strategy to reduce the magnitude of drying shrinkage is to provide moist curing and/or longer curing times.

The Silica Fume User Manual's instructions for mixing suggested having the silica fume pre-mixed with the water to create a slurry. This was also done with the Salt Lake City Airport Parking Garage and was created for all SCM mixtures in this study. The implementation of the slurry of the SCMs was anticipated to improve the dispersion of particles and could be investigated for how this mixing step may or may not improve the performance of the SCM.

5.4 Recommendations

The main recommendation from this research is for the Utah Department of Transportation to try implementing and monitoring bridge decks that contain silica fume concrete. There is a higher cost associated with the silica fume SCM because it is not locally available, so there are transportation/shipping costs, the material itself is also more expensive than other SCMs currently used, plus there would need to be possibly a higher water-reducing admixture dosage and more or longer curing performed on the bridge deck to ensure a successful finished and low cracked structure. The benefits of using the silica fume SCM are the lower CO_2 emissions, the higher life-cycle cost, and the stronger early strength allowing for traffic on the structure earlier.

5.5 Implementation Plan

The recommended next step would be to identify a bridge deck that is need of renovation or as a new structure in Utah. Work with a concrete materials supplier (ideally one who has already had experience with silica fume) to select the optimal amount of SCM (suggested as silica fume), and other mixture proportions for meeting a low or very low chloride resistance while checking shrinkage, strength, and workability properties. Ideally it would be useful from a research standpoint to have half the bridge deck be made with a different SCM (such as fly ash) so that these two sections can be monitored over time to further understand how the SCM performed in the Utah climate and salting of the same bridge deck. Most research professors in the area would be willing to monitor and provide a research write-up for this comparison study, which could be proposed through the UTRAC program.

REFERENCES

Alhajiri, A.M., and Akhtar, M.N. (2023) "Enhancing Sustainability and Economics of Concrete Production through Silica Fume: A Systematic Review." Civil Engineering Journal, Vol. 9, No. 10, October, pp. 2612-2629. http://dx.doi.org/10.28991/CEJ-2023-09-10-017

American Coal Ash Association. (2003). "Fly Ash Facts for Highway Engineers." FHWA-IF-03-019. Federal Highway Administration, Washington, D.C. https://rosap.ntl.bts.gov/view/dot/41258/dot_41258_DS1.pdf

Bang, K.M., Mazurek, J.M., Wood, J.M., White, G.E., Hendricks, S.A., Weston, A. (2015). "Silicosis Mortality Trends and New Exposures to Respirable Crystalline Silica — United States, 2001–2010." Morbidity and Mortality Weekly Report, 13 February 2015. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6405a1.htm

Bordelon, A., Clyde, M., and Gwynn, T. (2021) "Salt Lake City Airport Parking Garage Visual Inspection Report." Utah Department of Transportation Research Division, UT-21.23. August. https://rosap.ntl.bts.gov/view/dot/60279

Bordelon, A.C., and Cholleti, R.N.R. (2020). "Waste Glass Dust to Reduce Alkali Silica Reaction." 2020 Intermountain Engineering, Technology and Computing (IETC), 1-6. https://doi.org/10.1109/IETC47856.2020.9249128

Caltrans (2016). "Fly Ash: Current and Future Supply" Office of Structural Materials. Concrete Task Group and Rock Product Committees and Industry, https://purebase.com/wp-content/uploads/2020/07/Cal-Trans-Fly-Ash-Report-2016.pdf

Chancey, R.T., Stutzman, P., Juenger, M.C.G., and Fowler, D.W. (2010) "Comprehensive phase characterization of crystalline and amorphous phases of a Class F fly ash" Cement and Concrete Research. Volume 40, Issue 1, January, pp. 146-156. https://doi.org/10.1016/j.cemconres.2009.08.029

Detwiler, R.J., Mehta, P. K. (1989). "Chemical and Physical Effects of Silica Fume on the Mechanical Behavior of Concrete." ACI Materials Journal. Vol. 86, Issue 6, pp. 609-614. https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&i=2281

Ecosmart Concrete. (2021). "History." Ecosmart Concrete: A Concrete Contribution to the Environment. http://ecosmartconcrete.com/?page_id=250#:~:text=Fly%20ash%20was%20introduced%20commercially,the%20benefits%20were%20better%20understood

Expert Market Research (2024) "Fly Ash Market Size and Share Growth | Price Analysis 2023." https://www.expertmarketresearch.com/reports/fly-ash-market, Accessed 18 October 2024.

Fanijo, E. (2019) “Evaluation and Mitigation of Alkali Silica Reaction (ASR) in Cementitious Materials.” Master’s Thesis, University of Idaho. December. https://objects.lib.uidaho.edu/etd/pdf/Fanijo_idaho_0089N_11730.pdf

Federal Highway Administration. (2021). “FHWA Work Zone Facts and Statistics.” U.S. Department of Transportation Federal Highway Administration, 6 April 2021. https://ops.fhwa.dot.gov/wz/resources/facts_stats.htm#:~:text=Between%202018%20and%202019%2C%20fatal,zones%20decreased%20by%202%20percent

Fidjestøl, P., Dåstøl, M. (2020). “The History of Silica Fume in Concrete from Novelty to Key Ingredient in High Performance Concrete.” Norway. Elkem Materials. http://www.ibracon.org.br/eventos/50cbc/plenarias/per_fidjestol.pdf

Global Market Statistics. (2024a). “Concrete and Cement Statistics, Segment, Analysis Report 2032.” https://www.globalmarketstatistics.com/market-reports/concrete-and-cement-market-11086. Updated 30 September 2024.

Global Market Statistics. (2024b). “Silica Fume Market Size, Share & Growth | 2024-2032.” https://www.globalmarketstatistics.com/market-reports/silica-fume-market-10698. Updated 30 September 2024.

Hooton, R.D., Bentz, E., and Kojundic, T. (2010). “Long-Term Chloride Penetration Resistance of Silica Fume Concretes Based on Field Exposure.” Delft, University of Toronto. https://www.silicafume.org/pdf/reprints-longterm-resistance-concrete.pdf

Holland, T.C. (2005). “Silica Fume User’s Manual.” U.S. Department of Transportation and The Federal Highway Administration. April 2005. https://www.silicafume.org/pdf/silicafume-users-manual.pdf

Jeppsen, B. (2021). “Inquiry for Pumice Sample for UVU Research.” Message to Madison Clyde. 20 April 2021. Email

Krug H. F. (2022). “A Systematic Review on the Hazard Assessment of Amorphous Silica Based on the Literature From 2013 to 2018.” Frontiers in Public Health, 10, 902893. https://doi.org/10.3389/fpubh.2022.902893

Lair, J. (2020). “Contact Form.” Message to Madison Clyde. 4 December 2020. Email

Ley, T. and Cook, M. (2021). “A Professor’s Perspective: Is Fly Ash Going Away?” Aspire, Fall 2021, 48-49. https://aspirebridge.com/magazine/2021Fall/ProfessorsPerspective-IsFlyAshGoingAway.pdf

Lindquist, W.D., Darwin, D., and Browning, J.P. (2005) “Cracking and Chloride Contents in Reinforced Concrete Bridge Decks.” Kansas Department of Transportation, KTRAN KU-01-9. https://rosap.ntl.bts.gov/view/dot/40197

Lublóy, E., Czoboly, O., and Balázs, G.L. (2011). “Influence of Silica Fume on Fire Resistance.” Fib Symposium Conference, Prague, Czech Republic. June 2011. https://www.researchgate.net/publication/268515417

Malhotra, M. and Holland, T. (2022) “Point of View: Thoughts Regarding Cement, SCMs, Concrete, and CO2” Concrete International, Vol. 44, Issue 8, pp. 35-37. https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&id=51737128

Mallum, I, Rahman M.S., A., Lim, N.H.A.S, and Omolayo, N. (2021) “Sustainable Utilization of Waste Glass in Concrete: A Review.” Silicon. Volume 14, pages 3199–3214. https://doi.org/10.1007/s12633-021-01152-x

Meehan, C. (2017). “Momentum Recycling.” CompanyWeek, 17 April 2017, https://companyweek.sustainment.com/article/momentum-recycling/, Accessed 17 October 2024.

Mehta, P.K, and Monteiro, P.J.M (2014). “Concrete Microstructure, Properties, and Materials”. McGraw Hill Education, Fourth Edition, pages 139-144 and 313.

Merget, R., Bauer, T., Küpper, H. U., Philippou, S., Bauer, H. D., Breitstadt, R., & Bruening, T. (2002). “Health hazards due to the inhalation of amorphous silica.” Archives of toxicology, 75(11-12), 625–634. https://doi.org/10.1007/s002040100266

Miller, G.G., and Darwin, D. (2000) “Performance and Constructability of Silica Fume Bridge Deck Overlays.” Kansas Department of Transportation, SM Report No. 57. https://rosap.ntl.bts.gov/view/dot/42134

National Precast Concrete Association. (2017). “Fly Ash Trends Downward.” NPCA, 27 March 2017. https://precast.org/2017/03/fly-ash-trends-downward/#:~:text=With%20energy%20trends%20resulting%20in,availability%20has%20been%20significantly%20reduced.&text=But%20with%20the%20fly%20ash,silica%20fume%20and%20silicon%20dioxide

Norchem. (2011). "Silica Fume & Sustainability." Norchem, the Largest Producer of Silica Fume Products in North America. https://www.norchem.com/applications-sustainability.html

Olofinnade, O., Ndambuki, J., and Ede, A. (2017). “Experimental Investigation on the Effect of Elevated Temperature on Compressive Strength of Concrete Containing Waste Glass Powder.” International Journal of Engineering and Technology Innovation, 7(4), pp. 280-291. https://ojs.imeti.org/index.php/IJETI/issue/view/49

Pratt, T. W. (2024) “High-Performance Concrete Comprising Silica Fume: Evaluation of the Decommissioned Salt Lake City Airport Parking Structure” MS Thesis. Brigham Young University. https://www.acifoundation.org/Portals/12/Files/Resource%20Database/Trevor%20Pratt%20Thesis%20Gradprog%20Submission%20ETD%202024-04-16%20reduced.pdf

Ramasamy, U. (2014) “Alkali-silica reaction resistant concrete using pumice blended cement.” PhD Thesis, University of Utah. https://core.ac.uk/download/pdf/276263333.pdf

Ramasamy, U., Bordelon, A., and Tikalsky, P. (2017) “Properties of Different Pumice Grades Blended with Cement.” Journal of Materials in Civil Engineering, 29(7), March, 04017040. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001891

Sadiqul Islam, G.M., Rahman, M.H., and Kazi, N. (2016) “Waste glass powder as partial replacement of cement in sustainable concrete practice.” International Journal of Sustainable Built Environment 6, 37-44, 29 October 2016, Bangladesh. https://doi.org/10.1016/j.ijsbe.2016.10.005

Saha, A.K. (2018). “Effect of Class F Fly Ash on Durability Properties of Concrete.” Sustainable Environment Research, Volume 28, Issue 1, January, pp. 25-31. https://doi.org/10.1016/j.serj.2017.09.001

Saha, A.K., Khan, M.N.N., Sarker, P.K., Shaikh, F.A., and Pramanik, A. (2018) “The ASR mechanism of reactive aggregates in concrete and its mitigation by fly ash: A critical review.” Construction and Building Materials, Volume 171, pp. 742-758. https://doi.org/10.1016/j.conbuildmat.2018.03.183

Seraj, S., Cano, R., Liu, S., Whitney, D., Fowler, D., Ferron, R., Zhu, J., Juenger, M. (2014) “Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete”, Texas Department of Transportation, Report No. FHWA/TX-14/0-6717-1, October 2014. https://library.ctr.utexas.edu/ctr-publications/0-6717-1.pdf

Smith, D. (2021) “Inquiry for Ready Mix Prices.” Message to Madison Clyde. 13 January 2021. Email

Tariq, S., Scott, A.N., Mackechnie, J.R., and Shah, V. (2020). "Durability of High-Volume Glass Powder Self-Compacting Concrete." MPDI Applied Sciences. 10(22), 8058. https://doi.org/10.3390/app10228058

Value Market Research (2024) “Pozzolan Market Share, Analysis | Global Industry Report 2023.” https://www.valuemarketresearch.com/report/pozzolan-market. Accessed 18 October 2024.

Virtue Market Research. (2024) “Global Glass Recycling Market | Size, overview, trends, forecast | 2024-2030.” https://virtuemarketresearch.com/report/glass-recycling-market. Accessed 18 October 2024.

Whiting, D.A., Detwiler, R.J., and Lagergren, E.S. (2000). "Cracking Tendency and Drying Shrinkage of Silica Fume of Silica Fume Concrete for Bridge Deck Applications." ACI Materials Journal, February 2000. http://www.concrete.org/Publications/InternationalConcreteAbstractsPortal.aspx.aspx?m=details&i=808

Zier, M., Stenzel, P., Kotzur, L., and Stolten, D. (2021) "A review of decarbonization options for the glass industry." Energy Conversion and Management: X. Volume 10, June, 100083. https://doi.org/10.1016/j.ecmx.2021.100083

APPENDIX A: MATERIAL SPECIFICATIONS FOR CEMENTITIOUS MATERIALS

Below are descriptions related to each cementitious material. This includes information that was known about the manufacturer, location of manufactured product, amount obtained, date obtained, contact information from the manufacturer, and chemical or particle size information.

A.1 Type II/V Cement

This product comes from a company called LaFargeHolcim (formerly Holnam at the time of the SLC airport parking garage construction). It is manufactured at the Devil's Slide Cement Plant located at 6055 E. Corydon Rd, Morgan, UT 84050. The amount obtained was five 5-gallon buckets in February 2021. The contact was Todd Laker todd.laker@lafargeholcim.com. Safety requirements are to wear a mask when batching/mixing. A chemical analysis was not obtained. The specific gravity was assumed to be 3.15.

A.2 Silica Fume 1: R.E.D.

This product comes from a company called Reliable Efficient Dependable R.E.D. Industrial Products. It is stated to be manufactured at Mississippi Silicon LLC, 80 CR 210, Burnsville, MS 38833. The product name is 102DM. It is described by the manufacturer as a densified, amorphous light gray silica dioxide powder, obtained by filtering the dust extracted from the production of silicon metal in an electric arc furnace. The amount obtained was one 5-gallon bucket in January 2021. The contact was Bob Kedanis bkedanis@redindustrialproducts.com. Safety requirements are to wear a mask when batching/mixing. The chemical analyses provided by the manufacturer are as reported in Table A.1.

Table A.1 Chemical Composition of Silica Fume from R.E.D. Industrial Products

	typical from manufacturer	minimum	maximum
SiO_2	95%	93%	98.10%
Free C	1.50%	0.60%	3%
Free Si	0.12%	0.05%	0.20%
Total CaO	0.42%	0.19%	1.50%
SO_3	0.10%	<0.01%	0.50%
Na_2O	0.10%	<0.01%	0.50%
K_2O	0.38%	0.25%	0.80%
H_2O	0.30%	0.10%	1%
Al_2O_3	0.11%	<0.01%	0.50%
Fe_2O_3	0.12%	<0.01%	0.50%
MgO	0.29%	0.05%	0.60%
pH	7.8	6.75	8.8
Loss on Ignition (950°C during 1 hr.)	1.7%	1.1	3.7
BET Specific Surface (M^2/g)	20	18	22
Bulk Density (lb/ft^3)	40	30	47
>45 microns Size	2.2	0.5	8
Brightness L	47	45	50

A.3 Silica Fume 2: Euclid Chemical

This product comes from a company called Euclid Chemical based out of 19218 Redwood Road, Cleveland, OH 44110. The actual manufacturing location is not known. The product's name is Eucon MSA. It is described by the manufacturer as a powdered microsilica (silica fume). The amount obtained was one 50-pound bag in March 2020. The contact was Steven May smay@euclidchemical.com. Safety requirements are to wear a mask and eye protection when batching/mixing. A chemical analysis was not obtained but the technical data sheet states it has a microsilica content of 100%, an amorphous SiO_2 content of 92 to 98%, and a specific gravity of 2.20.

A.2 Silica Fume 3: GCP Applied Technologies

This product comes from a company called GCP Applied Technologies out of Cambridge MA. It is stated to be manufactured out of GCP Canada, 294 Clements Road W., Ajax, Ontario

L1S 3C6 Canada. The product's name is Force 10,000D. It is described by the manufacturer as a dry densified microsilica (silica fume) powder. The amount obtained was one 50-pound bag in Fall 2019. The contact was William (Bill) Jex william.m.jex@gcpat.com. Safety requirements are to wear a mask and eye protection when batching/mixing. A chemical analysis was not obtained. The specific gravity is reported by the manufacturer to be 2.20.

A.4 Fly Ash 1: Delta

This product comes from a company called Boral Resources, Delta UT. It is stated to be located out of South Jordan, UT 84095, (801) 984-9400 and manufactured at Delta, UT. The product's name is Coal Class F Fly Ash. The amount obtained was one 2.5-gallon bucket in January 2021. The contact was Doug Yeggy dyeggy@boral.com. Safety requirements are to wear a mask and eye protection when batching/mixing. The chemical analysis provided by the manufacturer are as reported in Table A.2.

Table A.2 Chemical Composition of Fly Ash from Boral Resources taken from Delta, Utah

SiO_2	59.64%
Al_2O_3	17.91%
Fe_2O_3	4.85%
SO_3	0.86%
CaO	8.20%
MgO	1.98%
Na_2O	1.88%
K_2O	1.26%
Moisture	0.04%
Loss on Ignition	1.44%
Density (g/cm^3)	2.2
Density of Water (g/cm^3)	1
Specific Gravity	2.2
>45 microns Size	19.40%

A.5 Fly Ash 2: Prairie States

This product comes from a company called Boral Resources, Prairie States. It is stated to be located out of Taylorsville, GA 30178 and manufactured at Platte River Power Authority, 2000 E Horsetooth Road, Fort Collins, CO 80525, (970) 266-4000. The amount obtained was one 5-gallon bucket in January 2021. The contact was Doug Yeggy dyeggy@boral.com. Safety requirements are to wear a mask and eye protection when batching/mixing. The chemical analyses provided by the manufacturer are as reported in Table A.3.

Table A.3 Chemical Composition of Fly Ash from Boral Resources from Prairie States

SiO_2	52.93%
Al_2O_3	17.34%
Fe_2O_3	10.61%
SO_3	2.73%
CaO	8.52%
MgO	1.42%
Na_2O	1.19%
K_2O	2.58%
Sodium Oxide Equivalent (Na_2O+0.658K_2O)	2.89%
Moisture	0.03%
Loss on Ignition	0.95%
Available Alkalis, as Na_2Oe	0.94%
Density (g/cm^3)	2.45
>45 microns Size	19.55%

A.6 Ultrafine Pumice

This product comes from a company called Hess Pumice. It is manufactured in Malad, Idaho. It is described by the manufacturer as amorphous (non-crystalline) in structure and is composed primarily of aluminum silicate. Pumice is a naturally calcined volcanic glass foam consisting of highly vesicular strands permeated with tiny air bubbles. The amount obtained was one 5-gallon bucket in January 2021. The contact was Brian Jeppsen brian@hesspumice.com. Safety requirements are to wear a mask when batching/mixing. The chemical analyses provided by the manufacturer are as reported in Table A.4.

Table A.4 Chemical Composition of Pumice from Hess Pumice (Jeppsen, 2021)

Silicon Dioxide	87.4%
Aluminum Oxide	10.52%
Ferric Oxide	0.194%
Ferrous Oxide	0.174%
Sodium	0.128%
Potassium	0.099%
Calcium	0.090%
Titanium Dioxide	0.0074%
Sulfate	0.00043%
Magnesium Oxide	0.126%
Water	1.11%
Hardness (MOHS)	6
pH	7.2
Water Soluble Substances	0.15%
Loss of Ignition	5%
Specific Gravity	2.35
GE Brightness	84
Crystalline Silica	None

A.7 Waste Glass Powder

This product comes from a company called Momentum Recycling. It is stated to be manufactured in Salt Lake City. The amount obtained was one 5-gallon bucket in January 2021. The contact was John Lair john@momentumrecycling.com. Safety requirements are to wear a mask when batching/mixing. A chemical analysis was not obtained. However, the same supplier of glass powder provided a sample reported in the study by Bordelon and Choletti in 2020. The chemical analysis of that sample by Bordelon and Choletti is shown in Table A.5.

Table A.5 Chemical Composition of Waste Glass Powder from Momentum Recycling (Bordelon and Choletti, 2020)

SiO_2	67.14%
Al_2O_3	1.48%
Fe_2O_3	0.51%
CaO	9.10%
MgO	0.64%
SO_3	0.06%
Na_2O	29.99%
K_2O	0.49%
Average Particle Size (μm)	23-39

APPENDIX B: AGGREGATE SIEVE ANALYSIS

Samples of each aggregate stockpile at Utah Valley University are assessed on a regular basis each fall. The following information is the measured weights on each sieve along with the average percent retained and cumulative percent passing for each aggregate. The coarse aggregate, sieve data shown in Table B.1, was a limestone ¾" nominal maximum aggregate size obtained from Geneva Rock. This meets ASTM C33 size #57. The fine aggregate, sieve data shown in Table B.2, is a natural sand obtained from Geneva Rock, and meets ASTM C33 fine aggregate size. The intermediate-size sieve data shown in Table B.3, is a limestone 3/8" nominal maximum aggregate size obtained from Geneva Rock. The intermediate size is too uniform graded to meet any ASTM standard.

Table B.1 Results of Sieve Analysis for Coarse Aggregate

Sieve		Sample Weight on Each Sieve						Average Percent Retained	Cum. Percent Passing
		Fall 2019 Group 2	Fall 2020 Group 1	Fall 2020 Group 2	Fall 2021 Group 5	Fall 2021 Group 2	Fall 2022 Group 1		
No.	**Mm**	lb	g	G	g	g	Kg	**%**	**%**
1"	**25**	0	0	0		24.8		**0%**	**100%**
3/4"	**19**	0.1185	28	18.5	126	2074.4		**12%**	**88%**
1/2"	**12.5**	6.2005	837	995	1901	1353.4	1.2624	**33%**	**55%**
3/8"	**9.5**	2.2055	1614.2	1608	1458	1076.4	0.4682	**25%**	**30%**
No. 4	**4.75**	2.2930	2296.4	2341.5	1240	148.7	0.2386	**27%**	**3%**
No. 8	**2.36**	0.1365	184	127		42.6	0.0199	**2%**	**1%**
Pan		0.0475	23.9	20.5	144	7	0.0124	**1%**	**0%**
Total		11.0015	4983.5	5110.5	4869	4995.5	2.0047	**100%**	

Table B.2 Results of Sieve Analysis for Fine Aggregate

Sieve		Sample Weight on Each Sieve							Average Percent Retained	Cum. Percent Passing
		Fall 2019 Group 4	Fall 2020 Group 3	Fall 2020 Group 4	Fall 2021 Group 3	Fall 2021 Group 4	Fall 2021 Group 7	Fall 2022 Group 3		
No.	**mm**	Kg	lb	g	g	lb	g	g	**%**	**%**
4	**4.75**	0.0146	0.025	8.8		0.02	1278.5	3.6	**2%**	**98%**
8	**2.36**	0.0997	0.08	34.3	57.7	0.173	1301	60.4	**7%**	**91%**
16	**1.18**	0.6474	0.872	280.5	97.5	0.749	2015	267.1	**27%**	**63%**
30	**0.6**	0.494	0.742	244.3	103.8	0.802	1295.5	323.9	**25%**	**38%**
50	**0.3**	0.3259	0.349	178.5	126.2	0.626	1083.9	217.4	**18%**	**20%**
100	**0.15**	0.2781	0.121	161.4	72.5	0.456	1011.7	119.5	**12%**	**8%**
200	**0.075**	0.1298	0.021	83.4	32		925.4	34.5	**5%**	**3%**
Pan		0.0124	0.003	9.3	9.9	0.154	862.1	6.5	**3%**	**0%**
Total		2.0019	2.214	1000.5	499.6	2.98	9773.1	1032.9	**100%**	

Table B.3 Results of Sieve Analysis for Intermediate Aggregate

Sieve		Sample Weight on Each Sieve				Average Percent Retained	Cum. Percent Passing
		Fall 2019 Group 1	Fall 2019 Group 3	Fall 2022 Group 2	Fall 2022 Group 4		
No.	**mm**	kg	G	g	g	**%**	**%**
3/8”	**9.5**	0.017	15.4	1.4		**0%**	**100%**
No. 4	**4.75**	0.91	1520.4	368.6	92	**39%**	**61%**
8	**2.36**	0.779	0	475	140.9	**31%**	**30%**
16	**1.18**	0.2	1357.4	109	47.4	**24%**	**7%**
30	**0.6**	0	0	24.4	11.2	**2%**	**5%**
50	**0.3**	0.0595	81.4	59.9	2.3	**3%**	**1%**
100	**0.15**	0	6.8	3.4	0.9	**0%**	**1%**
200	**0.075**	0	10.6	6.7	0.5	**0%**	**1%**
Pan		0.021	9.4	4.9	4.7	**1%**	**0%**
Total		1.9865	3001.4	1053.3	299.9	**100%**	

APPENDIX C: MIX DESIGNS AND FRESH AND HARDENED PROPERTIES OF PRE-TRIALS

Below are the concrete batch amounts along with any fresh and hardened properties measured from the earlier trials before a good mixture was selected for this study.

The first trial batches in this study included an intermediate aggregate with an NMAS = 3/8 in. However, these mixtures were clumpy, so the intermediate aggregate was removed from further trials in this study.

Table C.1 Aggregate Volume Ratios and Dosages for Admixtures Used in Pre-Trials

Trial	Aggregate Volume to Volume of Concrete	3/4" Coarse Aggregate	3/8" Intermediate Aggregate	Fine Aggregate	Air-Entrainer Dosage (fl.oz./100lb of cementitious)	Water-Reducer Dosage (fl.oz./100lb of cementitious)
2	70%	45%	20%	35%	0.48	2.87
3	65%	60%	0%	40%	1.36	2.74
4	65%	50%	0%	50%	0.92	2.77
5	68%	60%	0%	40%	2.32	3.86

Table C.2 Absorption Capacities (AC) Used for Pre-Trials

Trial	w/cm Ratio (at SSD condition)	AC of 3/4" Coarse	AC of 3/8" Intermediate	AC of Fine Aggregate	Weight of Water Added for OD to get to SSD (lb)
2	0.37	1.80%	3.2%	0.47%	1.97
3	0.38	1.80%	-	1.00%	1.29
4	0.43	1.80%	-	0.47%	1.23
5	0.38	1.80%	-	1.00%	1.29

Table C.3 Actual Oven-Dry Batched Weights of Pre-Trial 2

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾")	42.89
Intermediate Aggregate (NMAS = 3/8")	18.60
Fine Aggregate	32.85
Type II-V Cement	21.61
SCM: **4.5% Silica Fume**	1.004
Water	10.10
Air Entrainer (mL)	3.2
Water-Reducer (mL)	19.2

Table C.4 Actual Oven-Dry Batched Weights of Pre-Trial 3

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾”)	52.29
Fine Aggregate	34.71
Type II-V Cement	20.60
SCM: **9% Silica Fume**	2.00
Water	9.96
Air-Entrainer (mL)	9.1
Water-Reducer (mL)	18.3

Table C.5 Actual Oven-Dry Batched Weights of Pre-Trial 4

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾”)	44.31
Fine Aggregate	43.61
Type II-V Cement	21.01
SCM: **7.4% Silica Fume**	1.70
Water	11.02
Air-Entrainer (mL)	6.2
Water-Reducer (mL)	18.6

Table C.6 Actual Oven-Dry Batched Weights of Pre-Trial 5

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾”), dried	52.22
Fine Aggregate, dried	34.72
Type II-V Cement	17.60
SCM: 7.4% Silica Fume	1.73
SCM: 15% Fly Ash	3.41
Water	9.92
Air-Entrainer (mL)	15.6
Water-Reducer (mL)	26.0

Table C.7 Fresh Properties of Pre-Trials

Trial Number	SCM	Unit Weight (lb/ft^2)	Air (%)	Slump (in)
2	4.5% Silica Fume	146	2.4	1/4
3	9% Silica Fume	146	4.3	1/4
4	7.4% Silica Fume	144	4.2	1/2
5	7.4% Silica Fume + 15% Fly Ash	146	3.4	1/4

Table C.8 Compressive Strengths from Cylinders of Each Pre-Trial

Trial	7-day (psi)			**Average**	Standard Deviation	Coefficient of Variation
2	6560	7154	6727	**6814**	306	4.5%
3	7472	5348	7051	**6624**	1125	17% (high)
4	5977	4904	7180	**6020**	1139	19% (high)
5	6305	6158	3625	**5363**	1507	28% (high)
Trial	28-day (psi)			**Average**	Standard Deviation	Coefficient of Variation
2	10558	11047	8719	**10108 (high)**	1228	12%
3	8297	8280	6260	**7612**	1171	15%
4	3082	2311	7558	**4317**	2833	66% (very high)
5	9087	8068	8209	**8455 (high)**	552	7%

APPENDIX D: ACTUAL BATCH WEIGHTS OF EACH MIXTURE

Below is the actual batched out weights of materials for each final mixture used in the study.

Table D.1 Aggregate Volume Ratios and Dosages for Admixtures Used in Final Trials

Trials	Aggregate Volume to Volume of Concrete	3/4" Coarse Aggregate	3/8" Intermediate Aggregate	Fine Aggregate	Air-Entrainer Dosage (fl.oz./100lb of cementitious)	Water-Reducer Dosage (fl.oz./100lb of cementitious)
6 control	69%	60%	0%	40%	3.01	5.01
7-11	68%	60%	0%	40%	3.01	5.02
12-14	68%	60%	0%	40%	3.00	5.99

Table D.2 Absorption Capacities (AC) Used for Pre-Trials

Trials	w/cm Ratio	AC of 3/4" Coarse	AC of 3/8" Intermediate	AC of Fine Aggregate	Weight of Water Added for AC (lb)
6 control	0.38	1.80%	-	1.00%	1.29
7-11	0.39	1.80%	-	1.00%	1.29
12-14	0.38	2.00%	-	1.60%	1.60

Table D.3 Actual Oven-Dry Batch Weights for Trial 6 – Control

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾"), dried	52.20
Fine Aggregate, dried	34.71
Type II-V Cement	22.60
Water	9.91
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	33.5

Table D.4 Actual Oven-Dry Batch Weights for Trial 7 – Delta Fly Ash (FA1)

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾"), dried	52.19
Fine Aggregate, dried	34.80
Type II-V Cement	19.19
SCM: **15% Fly Ash**	3.41
Water	10.11
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	33.5

Table D.5 Actual Oven-Dry Batch Weights for Trial 8 – Prairie States Fly Ash (FA2)

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾”), dried	52.20
Fine Aggregate, dried	34.81
Type II-V Cement	19.14
SCM: **15% Fly Ash**	3.41
Water	10.10
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	33.5

Table D.6 Actual Oven-Dry Batch Weights for Trial 9 –R.E.D. Silica Fume (SF1a)

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾”), dried	52.20
Fine Aggregate, dried	34.81
Type II-V Cement	20.60
SCM: **9% Silica Fume**	2.00
Water	10.10
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	33.5

Table D.7 Actual Oven-Dry Batch Weights for Trial 10 – Pumice (PU)

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾”), dried	52.21
Fine Aggregate, dried	34.81
Type II-V Cement	19.21
SCM: **15% Pumice**	3.41
Water	10.11
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	33.5

Table D.8 Actual Oven-Dry Batch Weights for Trial 11 – Waste Glass Powder (WG)

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾”), dried	52.18
Fine Aggregate, dried	34.81
Type II-V Cement	19.10
SCM: **15% Waste Glass Powder**	3.40
Water	10.10
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	33.5

Table D.9 Actual Oven-Dry Batch Weights for Trial 12 – R.E.D Silica (SF1b)

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾"), dried	52.20
Fine Aggregate, dried	34.78
Type II-V Cement	20.64
SCM: **9% Silica Fume**	2.00
Water	10.20
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	40.1

Table D.10 Actual Oven-Dry Batch Weights for Trial 13 – Euclid Silica (SF2)

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾"), dried	52.27
Fine Aggregate, dried	34.81
Type II-V Cement	20.62
SCM: **9% Silica Fume**	2.05
Water	10.19
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	40.1

Table D.11 Actual Oven-Dry Batch Weights for Trial 14 – GCP Silica (SF3)

Material	Actual Batched Weight (lb)
Coarse Aggregate (NMAS = ¾"), dried	52.21
Fine Aggregate, dried	34.78
Type II-V Cement	20.62
SCM: **9% Silica Fume**	1.99
Water	10.22
Air-Entrainer (mL)	20.1
Water-Reducer (mL)	40.1

APPENDIX E: PHOTOS OF CONCRETE CYLINDER BREAKS AFTER COMPRESSION TESTS

In the trial batches, trial 5 and trial 9 both contained silica fume and significant amounts of honeycombing prior to testing. Images of these cylinders after testing at 7- and 28-days are shown in this section for trials 5 through 11. The mixtures containing the higher water-reducer and different silica fumes (trials 12-14) did not have honeycombing. Their pictures after testing are not shown here.

Figure E.1 Trial 5 - 7.4% Silica Fume, 15% Delta Fly Ash - Broken Cylinders after 7-Day Compression Strength Test.

Figure E.2 Trial 5 - 7.4% Silica Fume, 15% Delta Fly Ash - Broken Cylinders after 28-Day Compression Strength Test.

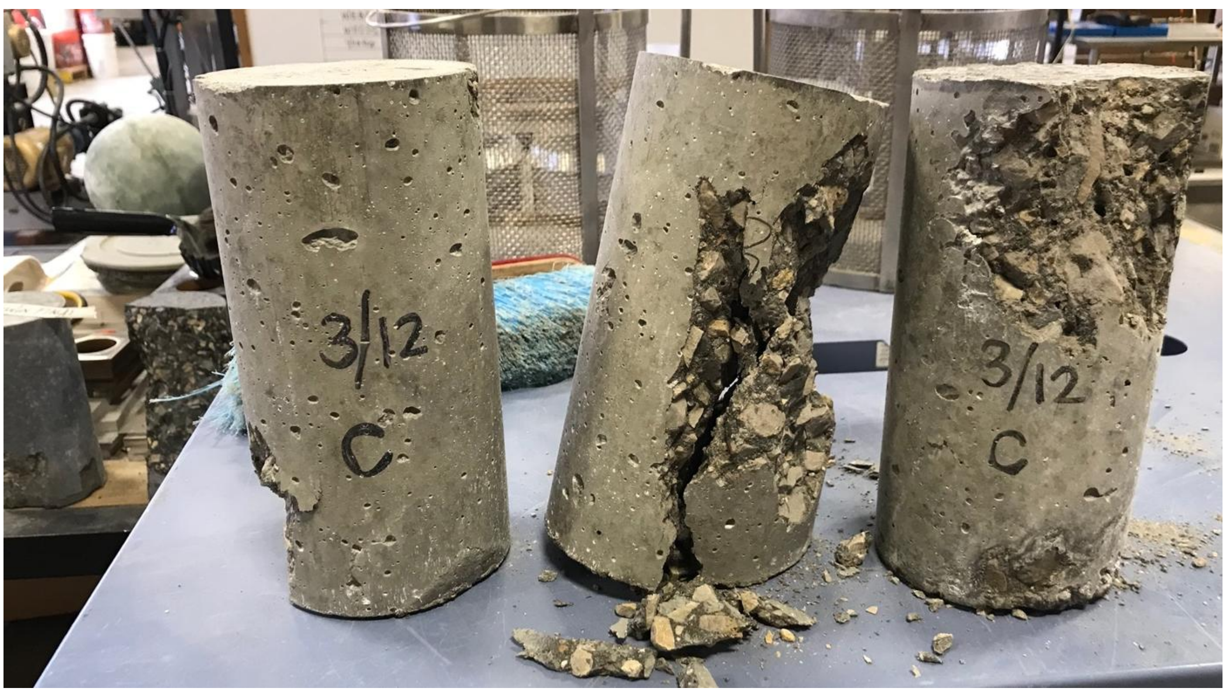


Figure E.3 Control – No SCM - Broken Cylinders after 7-Day Compression Strength Test.

Figure E.4 Control – No SCM – Broken Cylinders after 28-Day Compression Strength Test.

Figure E.5 Trial 7 – 15% Delta Fly Ash – Broken Cylinders after 7-Day Compression Strength Test.

Figure E.6 Trial 7 – 15% Delta Fly Ash – Broken Cylinders after 28-Day Compression Strength Test.

Figure E.7 Trial 8 – 15% Prairie States Fly Ash – Broken Cylinders after 7-Day Compression Strength Test.

Figure E.8 Trial 8 – 15% Prairie States Fly Ash – Broken Cylinders after 28-Day Compression Strength Test.

Figure E.9 Trial 9 – 9% Silica Fume – Broken Cylinders after 7-Day Compression Strength Test.

Figure E.10 Trial 9 – 9% Silica Fume – Broken Cylinders after 28-Day Compression Strength Test.

Figure E.11 Trial 10 – 15% Pumice – Broken Cylinders at 7-Day Compression Strength Test.

Figure E.12 Trial 10 – 15% Pumice – Broken Cylinders at 28-Day Compression Strength Test.

Figure E.13 Trial 11 – 15% Waste Glass Powder – Broken Cylinders after 7-Day Compression Strength Test.

Figure E.14 Trial 11 – 15% Waste Glass Powder – Broken Cylinders after 28-Day Compression Strength Test.