USE OF WASTE GLASS AS A SUPPLEMENTARY CEMENTITIOUS MATERIAL

by

Raja Nikesh Reddy Cholleti

A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering

The University of Utah

May 2015

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The thesis of **Raja Nikesh Reddy Cholleti**

has been approved by the following supervisory committee members:

Amanda C. Bordelon, Chair **19/12/2014**
Date Approved

Pedro Romero, Member **19/12/2014**
Date Approved

Steven Bartlett, Member **19/12/2014**
Date Approved

and by **Michael E. Barber**, Chair/Dean of

the Department/College/School of **Civil and Environmental Engineering**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

Millions of tons of generated glass are wasted each year and being added to landfills where it takes one million years to decompose. For companies that collect and recycle used glass, contamination from brown or multicolored-glass is more difficult to recycle than the clear glass form. Even among the collected glass, the less-demanded combined colored-glass is still often dumped into landfills. One alternate way to reduce the volume of waste materials being added to landfills is by using waste glass as a supplementary cementitious material (SCM). This alternative may also help in sustainability of the concrete industry by reducing the amount of cement needed in concrete, and thus reducing the amount of carbon emissions produced due to cement production. One challenge to using this waste glass in concrete is that sand-size glass or cullet when added to concrete will cause a cracking-causing expansive reaction referred to as "alkali-silica reaction" (ASR). However, glass also contains a significant amount of silica, which is a main component in many other supplementary cementitious materials that can improve the strength and durability of concrete. It is hypothesized that a finer particle size of the waste glass will drive the reactivity of the silica from the glass to occur earlier in concrete hydration rather than at the later ages when the detrimental reaction in concrete could occur.

This research focuses on determining the quantity and particle size at which waste glass powder can be effective in mortar against ASR. The probability of alkali-silica reaction is tested for mortar samples corresponding to ASTM C1567. Additional testing to verify the effect of the glass powder as a SCM on the compressive strength will be measured for mortar using ASTM C109/C109M. A separate common supplementary cementitious material called fly ash was also blended with the glass to examine whether it could provide beneficial combined effects on ASR and strength. It was found that the crushed mixed-colored glass, collected glass dust, or fly ash, when added alone or in combination, but equating to 40% replacement of cement was found to reduce the ASR expansion to the acceptable limits. However, at 10-40% waste glass dust percent replacements of cement, the 7-day compressive strength dropped by 68 to 42% compared to a mortar without any SCMs. The research also found that glass powder collected from the vacuum dust system at a crushing plant acts more effectively to reduce the effects of ASR as compared to the additionally crushed glass powder.

I dedicate this thesis to my family members especially…

my parents and also to my graduate advisor, Dr. Amanda Bordelon.

TABLE OF CONTENTS

LIST OF TABLES

NOMENCLATURE

- CG_0 represents mixed-colored crushed glass obtained as that passing through a 210 mesh at the glass recycling plant
- CG_3, CG_6, CG_9, CG_{12}, CG_{15}, CG_{30} and CG_{45} represent the same mixed-colored crushed glass but after it has been crushed with the cup pulverizer at the University of Utah for 3, 6, 9, 12, 15, 30, and 45 minutes, respectively
- GD represents the clear-and-green-colored glass dust taken from the dust vacuum collection system at the glass recycling plant
- FA represents Class F fly ash
- UFP represents ultra-fine pumice
- SF represents silica fume
- C represents Type II/V cement
- A mixture labelled 10% FA + 90% C represents a mortar mixture with 10% by weight of fly ash plus 90% cement and so on

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my graduate advisor, Dr. Amanda Bordelon, for her guidance and support throughout my research. In addition to research guidance, I learned the skills to execute work independently. Her valuable time, quick turnarounds, and high availability greatly helped me to be on the right track. Without her guidance and her persistent help I wouldn't have completed the research. I thank Dr. Pedro Romero and Dr. Steven Bartlett for their contribution as committee members.

I thank Uma Ramasamy, post-doctoral fellow in the civil engineering department, for giving me guidance on conducting tests. Also, I thank my friend, Chalapathi Uppala, for conducting tests for me during a time of my absence.

I thank Wade Stinson for helping me to pick up the glass samples from the glass recycling plant. Further thanks to Mark Bryant in the civil engineering department for his assistance in supplying the materials required for testing.

A special thanks to my parents and my loving brother for supporting me in every aspect. Without support from my family, this thesis would not have been possible.

CHAPTER 1

INTRODUCTION

1.1. Waste Glass Recycling

Recycling of contaminated waste has become a major environmental problem that includes waste glass as it is nonbiodegradable in nature and there is a low percent of recovery from landfills [1]. Glass from bottles can take more than a million years to decompose [2]. Thus it is beneficial to reduce the amount of glass that is disposed of in landfills because of the volume it will occupy along with the long decomposition rate. The total municipal solid waste glass generated in 2010 was calculated to be about 11.5 million tons [1]. Out of which 80% by weight of the waste glass collected is soda-lime glass widely used to manufacture containers [3]. Fifty percent of the solid waste glass stream originated as containers for beer and soft drinks with the remaining 50 % as containers for wine, other liquors, and various other containers or goods/products [1]. A single person is anticipated to use an average 82 pounds of glass each year [4]. According to the United States Environmental Protection Agency, more than 11.78 million tons of glass is generated in the US [5]. Of which, 11,530 thousands of tons of glass are generated annually [6]. Roughly 8,590 thousand tons of glass is not being recycled but instead filling up landfills in the US. Of all the collected waste glass, only 25.5% is recycled [5]. A significant amount of effort is made by recycling plants to sort and separate the different glass colors.

Compared to other colors, clear glass can be recycled and re-melted at lower energies back into its pure form without any reduction in quality [7, 8]. Waste clear-glass cullet is also used in fiber insulation industries where the can be recycled into structural fiber glass. Thus, non-contaminated recycled clear-colored glass has a high market demand. The mixed-colored or un-sorted glass is difficult to recycle into the more desirable clear glass form. As a result, the less-demanded colored glass and combined multiple-colored glass collections are often dumped into landfills.

1.2. Waste Glass in Concrete

Many researchers have tried to find a way to effectively use waste glass in the construction industry. Potential alternative uses for such waste glass would be to add it into concrete or as a base course construction material [9, 10]. The alternative with using glass in concrete could be a viable sustainable option if glass could replace some portion of the cement needed in concrete, and may reduce the amount of carbon emissions produced due to reduced cement production demand.

Several past researchers have found that cullet-size clear or white glass has been proven to create detrimental expansion and cracking problems if added to concrete [9, 11, 12]. This expansive reaction is referred to as “alkali-silica reaction” (ASR). This ASR expansion is linked to the alkali content from the glass and reactive aggregate dissolving reactive amorphous silica from glass in the presence of moisture at high $pH > 12$ [13]. The expansion occurs when there are high alkali contents, free calcium ions, particles with reactive silica often from aggregates or glass cullet, and the presence of water. Most ASR reactions occur after a long period of time, but the expansive ASR gel product weakens or cracks the concrete.

Some researchers have investigated the rate and presence of ASR from different colored-glass cullet as a replacement of fine aggregates in concrete [10, 14, 15]. In fact since cullet glass has been found to consistently produce this ASR reaction, a clear glass cullet is required as the worst-case scenario reference material for many ASR test standards. Of the colors tested, green-colored glass has been found to create less ASR expansion than clear glass [9, 11]. There is no definite trend on whether green-colored glass alone produces better or worse ASR expansions compared to brown glass [12].

Researchers used mixed colored-glass as a coarse aggregate material where it did not give a substantial benefit to expansion and shrinkage [10]. Some researchers also studied using different colored-glass cullet as fine aggregate, which have predominantly indicated significant ASR expansion with clear glass [9, 11, 12]. Researchers also found that glass, when crushed to a finer particle size and used as a SCM, showed incremental increases in strength [16, 17] and also exhibited pozzolanic behavior as glass particles size goes down. At this finer particle size it is believed that the free calcium in cement reacts effectively with amorphous silica in glass at early ages in the presence of moisture and forms C-S-H gel, which helps concrete or mortar to exhibit pozzolanic behavior.

1.3. Research Objectives

In this research, a powder form of waste glass will be used like a supplementary cementitious material (SCM) in order to determine whether the ASR expansion is below specified limits and to understand the influence on compressive strength. The waste glass contains a significant amount of silica which is common in many other supplementary cementitious materials because the silica can chemically react with free calcium at early ages for improved strength and durability of concrete. Several SCMs can be manufactured to be more effective for these concrete performance benefits if it is a finer particle size. Since it is known that waste glass, when used as a sand-size cullet particle, will cause ASR, it is instead hypothesized that a finer particle size will drive the reactivity of the silica from the glass to occur earlier, forming calcium silica hydrate gel rather than at the later ages as ASR gel. This research investigates what quantity and size of waste glass, when crushed and added as a fine supplementary cementitious powder, can be used to reduce the probability of ASR in mortar beams while also potentially improving the strength of the mortar cubes. This research also includes using a glass dust, as collected air-borne fines from crushing at the recycling glass plant. A summary of the objectives are as follows:

1. To measure and provide recommendations that meet the ASTM limits for the potential ASR expansion, by varying mortar mixtures with the following:
    - Glass dust, crushed glass powders, and fly ash alone or in combination as SCMs (up to 40% replacement of cement)
    - 15% replacement of cement as either crushed glass with varying crushing times, or alternative pozzolans
2. To measure the change in compressive strength for mortar mixtures:
    - With varying the amount of glass dust, crushed glass powder, fly ash, or combinations of these SCMs
3. To perform a quantity and cost comparison between cement and glass powder used as a SCM for the state of Utah.

CHAPTER 2

MATERIALS AND TESTING METHODOLOGY USED

2.1. Waste Glass Production

2.1.1. Plant collection and crushing process

The Momentum glass recycling plant in Salt Lake City is the only plant in the state of Utah that crushes recycled waste glass. The waste glass is collected from residential, commercial, and public sectors with 20 collection points in Salt Lake City and 8 drop-off locations in neighboring towns within 1 hour of Salt Lake City. On average, the recycling plant receives 300-400 tons of waste glass per month. Clear- and green-colored glass is the main source of income to the plant. As such, the different colors are sorted out manually from the collected waste glass stream, crushed to fine sizes, and sold to various demanding markets. The brown or other "colored-glass" is also crushed and currently stock-piled or landfilled. The percentage of each crushed glass size created at the plant's crushing facilities is shown in Table 2.1.

The finest product that the company currently sieves out is a 210 microns minus, which accounts for only 15% of overall collection of the mixed-colored waste glass. To obtain much finer sizes, the recycling plant would require either additional machinery to crush the glass cullet finer, or to possibly run the material through existing crushing equipment for longer crush times.

Table 2.1 Amount of Each Sieve Size of Glass from Recycled Plant Crushing

	Brown/Mixed-Colored Glass	Clear- and Green-Colored Glass
Passing 1.7mm	-	85-90%
840 to 420 microns	50%	-
420 to 210 microns	25%	-
210 microns minus	15%	-
Dust (210 microns minus)	10%	10-15%
Total Quantity	100%	100%

For this research, it is hypothesized that a particle size of the glass would need to be finer than the 210 minus supplied by the plant in order for this glass to behave similar to a SCM. Some of glass dust, which is collected from the plants vacuum system was also analyzed for this research. The glass dust (GD) collected from the plant was directly used for this research without any further crushing.

2.1.2. University of Utah concrete lab crushing process

The "raw" mixed-colored crushed glass of sizes 210 minus CG_0 were subjected to additional crushing in the University of Utah concrete laboratory. A vibrator cup pulverizer was used to further crush the glass CG_0 at different timings. Initially, CG_0 was crushed in incremental time intervals from 3, 6, or 9 minutes. The 12 minute crushed glass CG_{12} was crushed in two 6-minute increments. The particle sizes for these along with the glass dust are shown in Figure 2-1. Additional crushing was done at intervals of either 15 minutes CG_{15}, 30 minutes CG_{30}, or 30 and then 15 additional minutes CG_{45}.

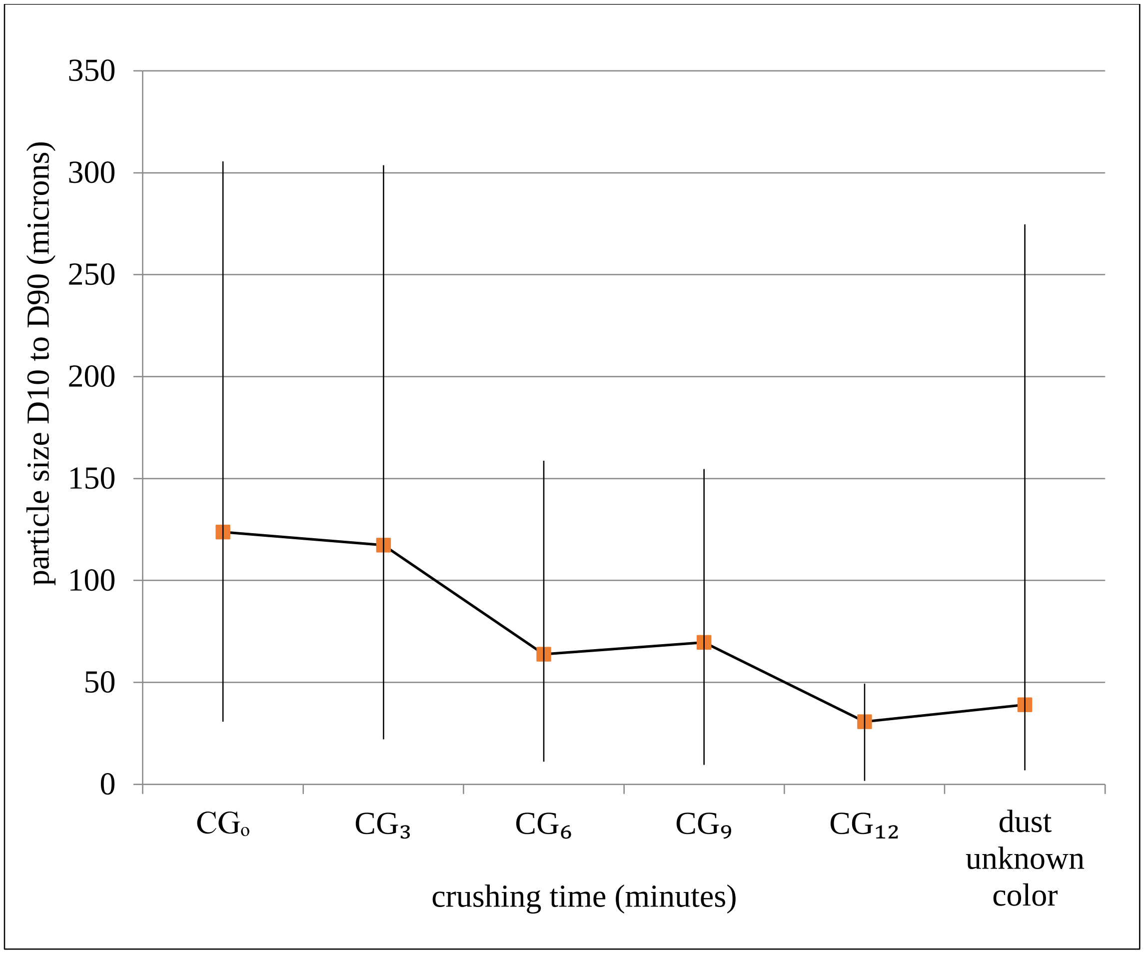

Figure 2-1 Particle size of glass powders at different crushing timings as analyzed by Hess Company. Showing 10, 50, and 90% cumulative passing sizes.

The particle sizes for these are summarized in Table 2.2, shown as a gradation curve plot in Figure 2-2, and as a plot of crushing time versus percent passing of 10, 50 and 90 in Figure 2-3. It was observed that glass particles found near the inner ring within the cup pulverizer's three ring bins were more agglomerated. These agglomerated particles were not used in the research mixtures for this project. It is unknown as to why the CG_{30} shows a slightly larger particle size. However, it was hypothesized to be related to the sequence of incremental crushing which may have re-oriented particles to have more effective crushing.

Table 2.2 Average Particle Sizes of Materials Used in Study

Material Type	Mean (µm)	Median (µm)	Mode (µm)	Passing 45 (µm)
Clear- and Green-Colored Glass Dust (GD)	48.367	22.546	21.374	68.6%
No Crushed (210 micron minus) (CG_0)	180.215	152.099	187.143	12.6%
12 Minutes Mixed-Colored Crushed Glass (CG_{12})	41.930	24.680	27.872	67.5%
30 Minutes Mixed-Colored Crushed Glass (CG_{30})	53.220	39.039	82.441	54%
45 Minutes Mixed-Colored Crushed Glass (CG_{45})	40.464	25.479	63.140	66.6%

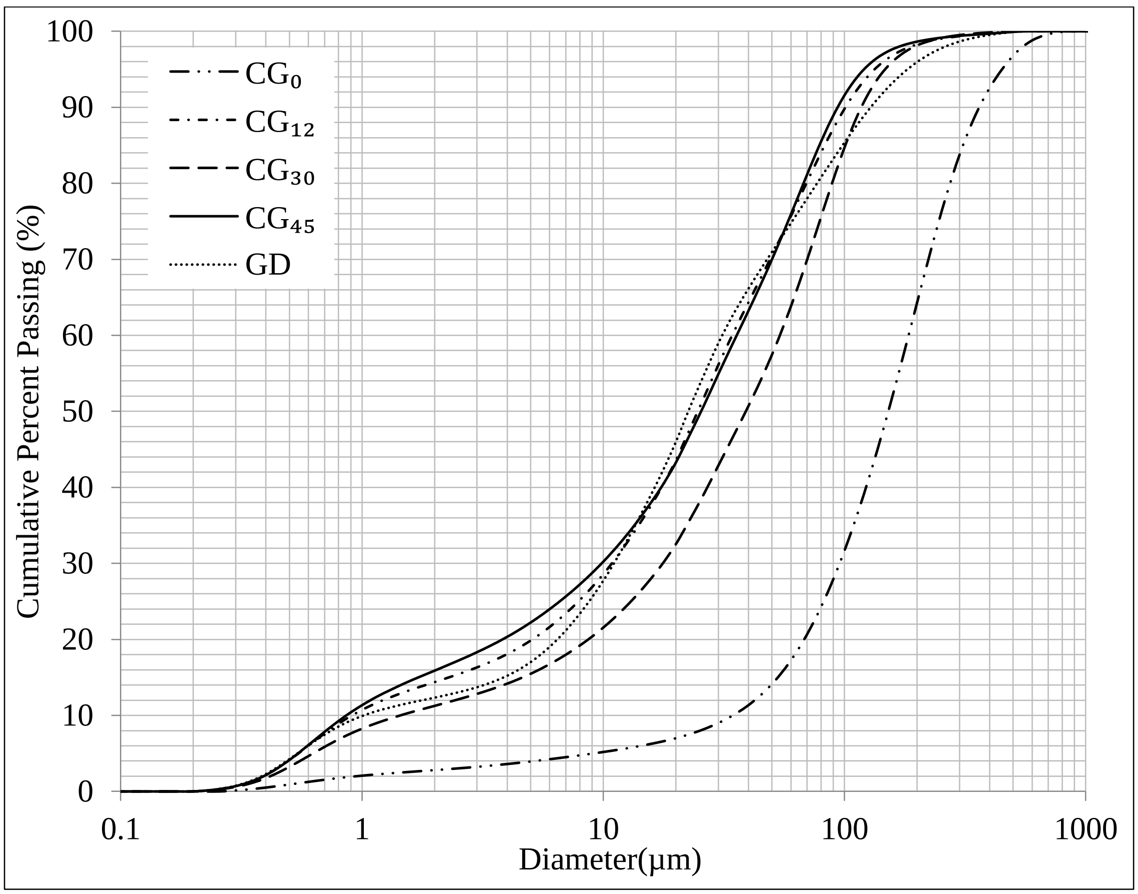

Figure 2-2 Particle size distribution of waste glass at different crushing times.

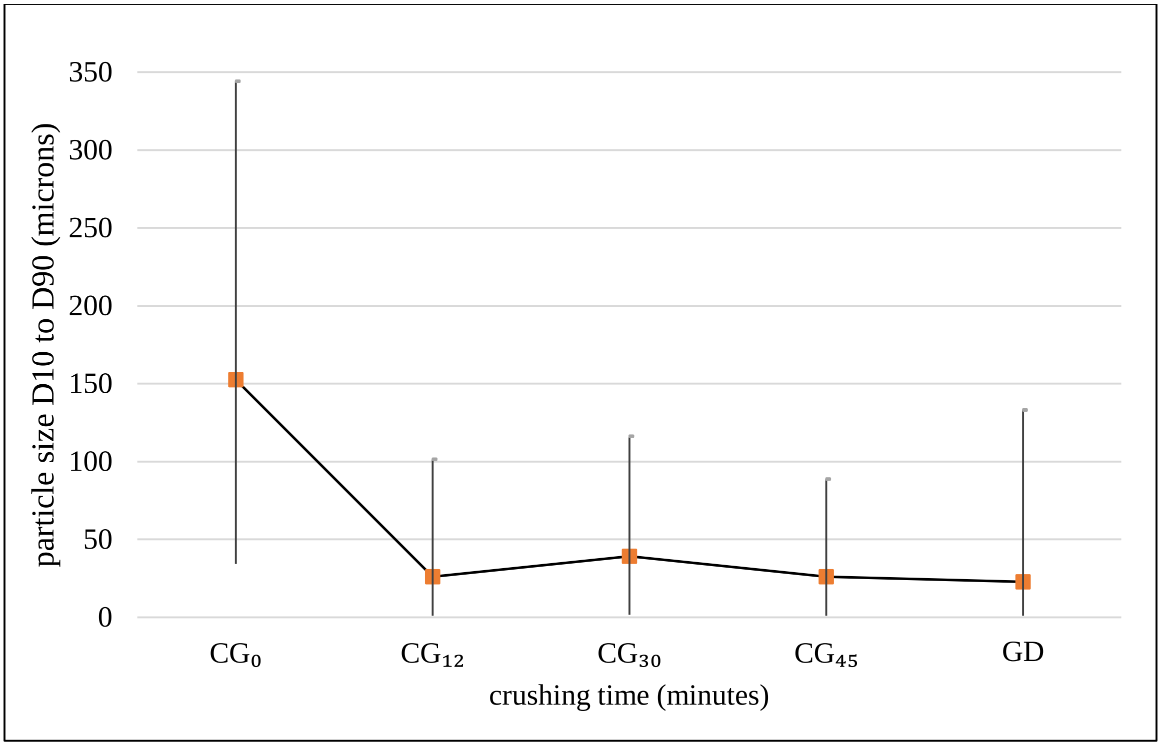

Figure 2-3 Particle size of glass powder for different crushing timings as analyzed at Oklahoma State University.

Slight differences in particle size between the analyzed samples is expected. This is due to natural variability in the raw glass material as well as possible sampling errors from the additional lab crushing, or even different accuracies associated with using two different analysis devices. Despite this, it does appear overall (Figure 2-4) that by 12 minutes crushing in this type of vibratory cup pulverizer, the mean size of glass did not significantly change with additional crushing. This mean size appeared to average around 40-53µm.

The glass dust as collected in the vacuum system in the plant is expected to have the highest variability but to also be much finer. The mean, median and mode of GD are all low around 21-48µm, while there is still a few larger particles (90% of the particles are 133µm or less).

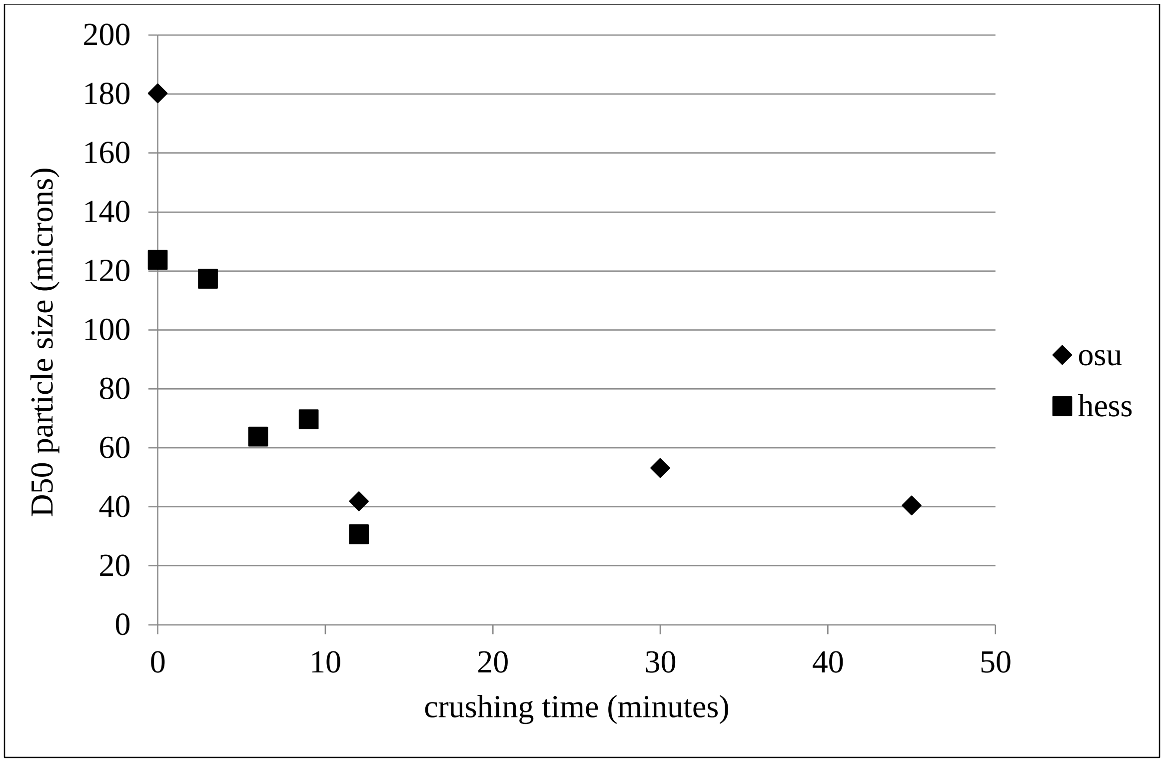

Figure 2-4 Comparison of mean (D50) particle size of different crushing timings analyzed at different laboratories.

2.2. Materials Used in Mortar

2.2.1. <u>Waste glass powders</u>

The waste glass material for this research was collected from the Momentum Company recycling plant in Salt Lake City. Its “raw” form was obtained after the plant had sorted it, crushed it, and sieved it to passing through a 210 micron sieve. For this research, this sieved glass originated from a mixed-colored glass pile in which the majority of clear- and green-colored glass was manually removed during sorting. The sieved glass was further crushed at the University of Utah campus to a finer powder. This finer crushed glass is labelled CG. A separate collection of glass dust was also used in this research, labelled as GD. This glass dust was collected from the dust vacuum system at the plant on a clear- and green-colored crushing day. The clear- and green-colored glass is expected to have less reactivity to ASR than the mixed-colored crushed glass, which contains more brown-colored glass that other researchers found more reactive. The mix designs were cast with CG_0, CG_{12}, CG_{30}, CG_{45} and GD.

2.2.2. Cement and other SCMs

A standard Type II/V Portland cement (PC) [18] was obtained from the Ash Grove cement plant in Nephi, Utah and used for strength and ASR testing. Fly ash is the commonly used SCM in the region for durability and cost benefits. Headwaters Company Navajo Class-F standard fly ash (FA) [19] was used for a comparison SCM, as well as in combination with waste glass powder. Silica fume is known for being an effective pozzolan for strength and durability, W.R. Grace’s Force 10,000 D densified silica fume powder (SF) [20] is used for a comparison with ASR testing. Pumice has been recently discovered to provide a low ASR expansion performance; therefore, ultra-fine pumice (UFP) from Hess Pumice in Malad, Idaho were also used for a comparison with ASR testing. A summary of the particle sizes and chemistry for these materials based on particle size analyzer and X-ray fluorescence (XRF) can be seen in Table 2.3.

2.2.3. Aggregates

A low-reactive aggregate was hypothesized to produce mortar samples with negligible ASR expansion values. Thus, moderately-reactive or highly-reactive aggregates were expected to create detrimental expansion above the ASTM [21] acceptable limits. Of the fine aggregate sources in the Salt Lake Valley, the natural sand originating from Beck, Utah was selected. This is because it is local and has been found to be moderately-reactive to ASR [22] and was used as a fine aggregate for the ASR testing of this research.

Table 2.3 Summary of Cementitious Materials in this Study

	Cement Type II[22]	GD	CG_{30}	FA [23]	SF [20]	UFP [22]
Average Particle Size (μm)	~11	48	53	~20-25	1-2	3.99
SiO2	20.67	69.14	69.89	59.58	> 85	69.75
Al2O3	3.97	1.48	1.38	22.08	-	11.18
Fe2O3	3.65	0.51	0.38	4.65	< 5	1.04
CaO	63.57	9.10	9.48	5.29	< 5	0.97
MgO	1.55	0.64	0.36	-	< 5	0.25
SO3	2.81	0.06	0.05	0.43	-	-
Na2O	0.06	29.99	31.25	1.3	-	2.34
K2O	0.72	0.49	0.48	-	-	4.79
Cl	0.018	-	-	-	-	-
Total	98.43	111.49	113.34	93.33	-	90.42

For this ASR testing, the natural sand was regraded to meet the ASR test standard requirements [24]. For the strength and flow testing, a graded Ottawa sand [25] was used instead.

2.2.4. Chemical admixture

The amount of water-reducer added to the mortar mixture varied in order to maintain the same workability among all mixtures. The advantage of adding this type of high range water-reducer to a mixture is that it has no effect on strength of the concrete. BASF's Glenium 7710 [26] classified as type-F high-range water-reducing admixture [27] was used to maintain the flow of different mortar mixtures for strength.

2.3. Mix Designs

Various batches of mortar were studied for both compressive strength of mortar cubes and alkali-silica reaction of mortar bars. The specific SCM combinations tested in this research for either ASR or strength tests are summarized in Table 2.4. These batches contain different proportions (0%, 10%, 15%, 20% and 40% of total cementitious material by weight with the other combination cementitious material). Mechanical mixing of the hydraulic cement paste for both compressive strength and ASR are conducted in a Hobart pan mixer according to [28].

2.4. Testing Methods

2.4.1. Flow properties

All the mix designs tested for compressive strength were first tested for the flow properties according to mortar workability tests [29]. All mixtures that did not achieve a flow number near 17 were either redone or added to with varying amounts of the high-range water-reducing admixture.

The flow test equipment standards were maintained according to [30]. Figure 2-5 and Figure 2-6 show the final flow consistency and final amount of Glenium-7710 added to obtain the flow consistency for each mixture, respectively.

There was no consistent trend found for the relationship between flow number and HRWR dosage versus SCM type of amount. Average and standard deviation for the flow number among all mixtures are 17.06 and 1.33, respectively. Overall variation in flow number was 7.8% between all mixtures.

Table 2.4 ASTM Standard Tests Conducted (X) on Mix Designs for Strength and ASR

% Cement Replacement by mass	Strength*	A-S-R**
Control Mix	X	X
90% C + 10% FA	X	X
85% C + 15% FA	X	X
80% C + 20% FA	X	X
60% C + 40% FA	-	X
85% C + 15%CG_0	X	X
90% C + 10% CG_{12}	X	X
85% C + 15% CG_{12}	X	X
80% C + 20% CG_{12}	X	X
60% C + 40% CG_{12}	-	X
85 % C + 15% CG_{30}	X	X
85% C + 15% CG_{45}	X	X
90% C + 10% GD	X	X
85% C + 15% GD	X	X
80% C + 20% GD	X	X
60% C + 40% GD	X	X
80% C + 10% CG_{12} + 10% FA	X	X
70% C + 15% CG_{12} + 15% FA	X	X
60% C + 20% CG_{12} + 20% FA	X	X
80% C + 10% GD + 10% FA	X	X
70% C + 15% GD + 15% FA	X	X
60% C + 20% GD + 20% FA	-	X
85% C + 15% SF	-	X
85% C + 15% UFP	-	X

* 3 replicates made of each mixture and each age tested (3, 7, 28, 91 days).
** 4 replicates made of each mixture (all tested at ages 3, 6, 9, 12, 14 days after submersion in NaOH solution).

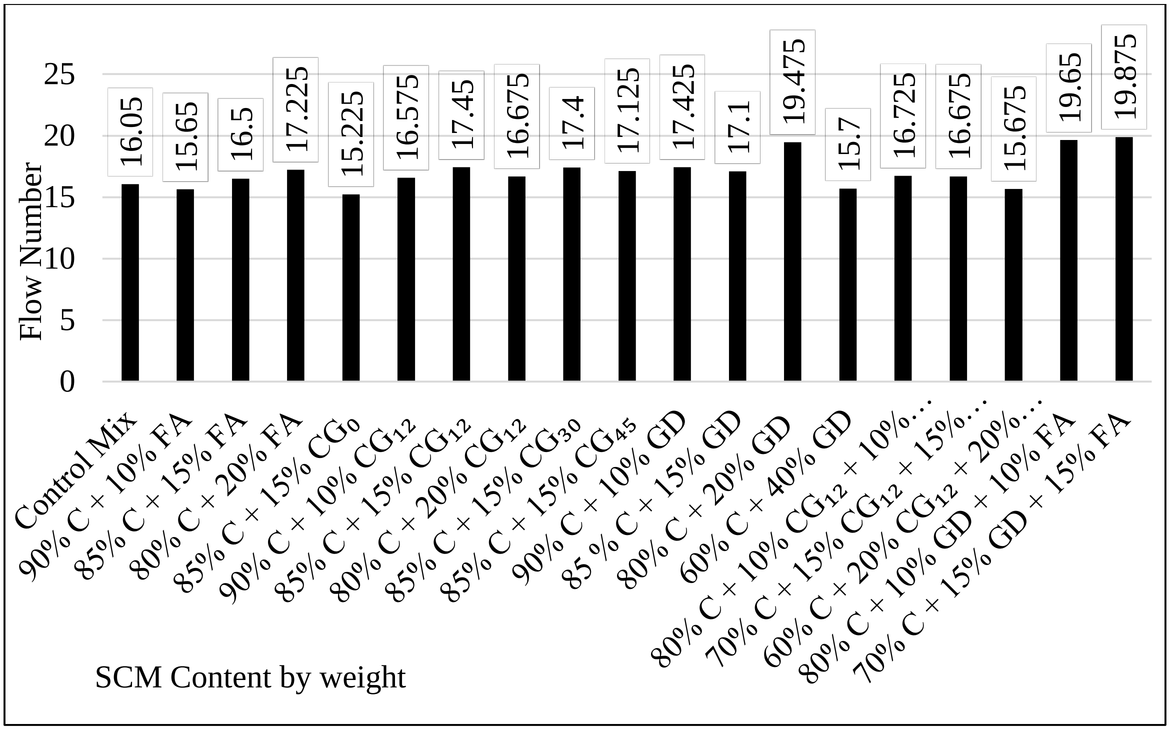

Figure 2-5 Average flow reading according to ASTM [29] for various mixtures; 4 readings each.

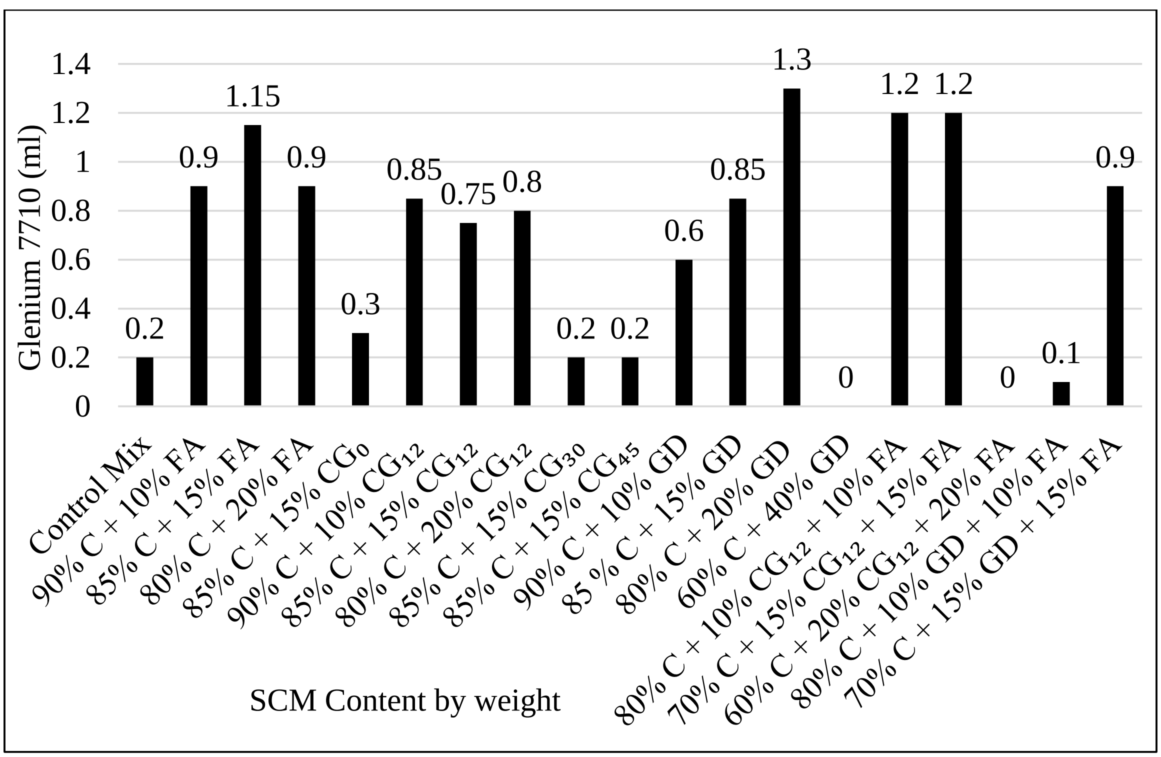

Figure 2-6 Final amount of Glenium 7710 added to various mix designs to produce an average of 17+/-3 flow number.

2.4.2. Compressive strength

Compressive strength tests on the mortar are conducted according to [31] on 2 inch cubes for various ages of 3, 7, 28 and 91 days, to understand the strength development curve. Three replicate cubes were tested at each age for each mixture. All the samples are immersed in saturated lime water and stored in a moist room. ASTM [31] states that the maximum coefficient of variation (COV) for any age should be either 8.7% for three samples or 7.6% for two samples.

2.4.3. ASR potential

The potential of ASR was determined on (1 inch*1 inch*10 inch) mortar bars by using an [23] ASTM C1567 test method. This method is an accelerated test, designed to evaluate SCMs for reducing ASR. A separate similar standard that does not include SCMs is ASTM [21], which instead is used by the industry to determine the aggregate reactivity to ASR. These tests are performed in an aggressive environment of 80°C and a 1 M NaOH solution to speed up the potential ASR. Mortar bar samples will be measured for expansion at 3, 6, 9, 12, 14 days of immersion in the aggressive solution environment. Samples expanding more than 0.1% in length after 14 days immersion (16 day age) are considered susceptible to ASR. The control mixture containing 0% SCM and a moderately-reactive aggregate is expected to expand more than 0.1%. Four replicate mortar beams were tested of each mixture. An acceptable COV for the mortar bar ASTM [23] test is either a COV < 2.94% based on 3 samples, or COV < 8.3% based on 2 samples.

CHAPTER 3

ASR AND STRENGTH RESULTS

3.1. ASR Expansion

3.1.1. Effect of fly ash, glass dust, and crushed glass

Average 14-day immersion accelerated ASR expansion levels for various mix designs of fly ash, glass dust, and 12-minutes crushed glass are shown in. Table 3.1. The plots of the ASR expansion versus time for each of the SCMs fly ash, glass dust, and 12-minutes crushed glass are shown in Figure 3.1, Figure 3.2, and Figure 3.3, respectively. The highest percentage expansion for 16-days is seen for the 100% cement control mortar mixture at 0.43%. In general, all of the SCMs reduced the ASR expansion, even the glass powders, and as the amount of SCM increased, the magnitude of expansion decreased. The use of glass powders or even fly ash at lower replacement rates of up to 20% was not enough to slow the expansion below the 0.1% expansion limit. So, to understand the linear expansion behavior of fly ash, a glass powders regression curve is plotted in Figure 3-4 for the mix designs with 10%, 15% and 20% replacement of fly ash and glass powders. This regression analysis indicated that a possible 40% replacement of cement by fly ash or glass dust may be sufficient to reduce ASR below the ASTM standard limit. Additional samples were tested at this 40% replacement and a new regression curve is updated, including the 40% of fly ash, glass dust, and crushed glass, as seen in Figure 3-5.

Table 3.1 Length Change Statistics due to ASR for Various SCM Combinations

SCM Combinations with % Binder	ASR Expansion of 4-mortar bars after 14-day immersion in NaOH solution (%)		
	Average	Standard Deviation	COV
Control Mix (100% C)	0.4368	0.0204	4.69
90% C + 10% FA	0.4625	0.0077	1.682*
85% C + 15% FA	0.2855	0.009	3.152
80% C + 20% FA	0.2295	0.0147	6.418
60% C + 40% FA	0.0495	0.0021	4.285*
85% C + 15% CG_0	0.3627	0.0059	1.629
90% C + 10% CG_{12}	0.3660	0.0188	5.150
85% C + 15% CG_{12}	0.3530	0.0236	6.691
80% C + 20% CG_{12}	0.3153	0.0176	5.586
60% C + 40% CG_{12}	0.1017	0.0040	3.961
85% C + 15% CG_{30}	0.3258	0.0179	5.510
85% C + 15% CG_{45}	0.3585	0.0152	4.257
90% C + 10% GD	0.3110	0.0104	3.372
85% C + 15% GD	0.2625	0.0134	5.106
80% C + 20% GD	0.2328	0.0078	3.353
60% C + 40% GD	0.0455	0.0007	1.554*
80% C + 10% CG_{12} + 10% FA	0.2678	0.0049	1.839
70% C + 15% CG_{12} + 15% FA	0.1285	0.0064	4.953*
60% C + 20% CG_{12} + 20% FA	0.034	0.0014	4.159*
80% C + 10% GD + 10% FA	0.19	0.00142	1.132*
70% C + 15% GD + 15% FA	0.0815	0.00495	6.073*
60% C + 20% GD + 20% FA	0.036	0.00283	7.856*
85% C + 15% SF	0.1213	0.0084	6.977
85% C + 15% UFP	0.017	0.0014	8.3*

* Average, standard deviation and coefficient of variance (COV) counted for 2 mortar bars only to verify COV < 8.3% according to ASTM [23].

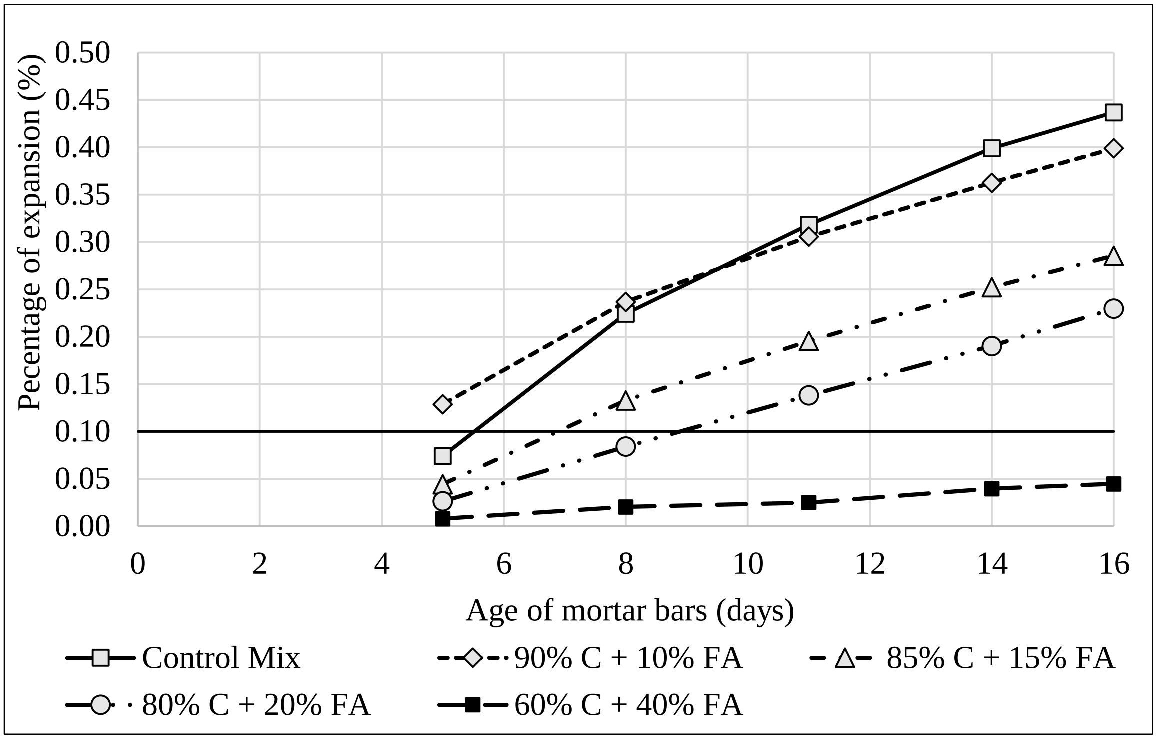

Figure 3-1 Average expansion for all mixtures containing fly ash; 4 replicates each.

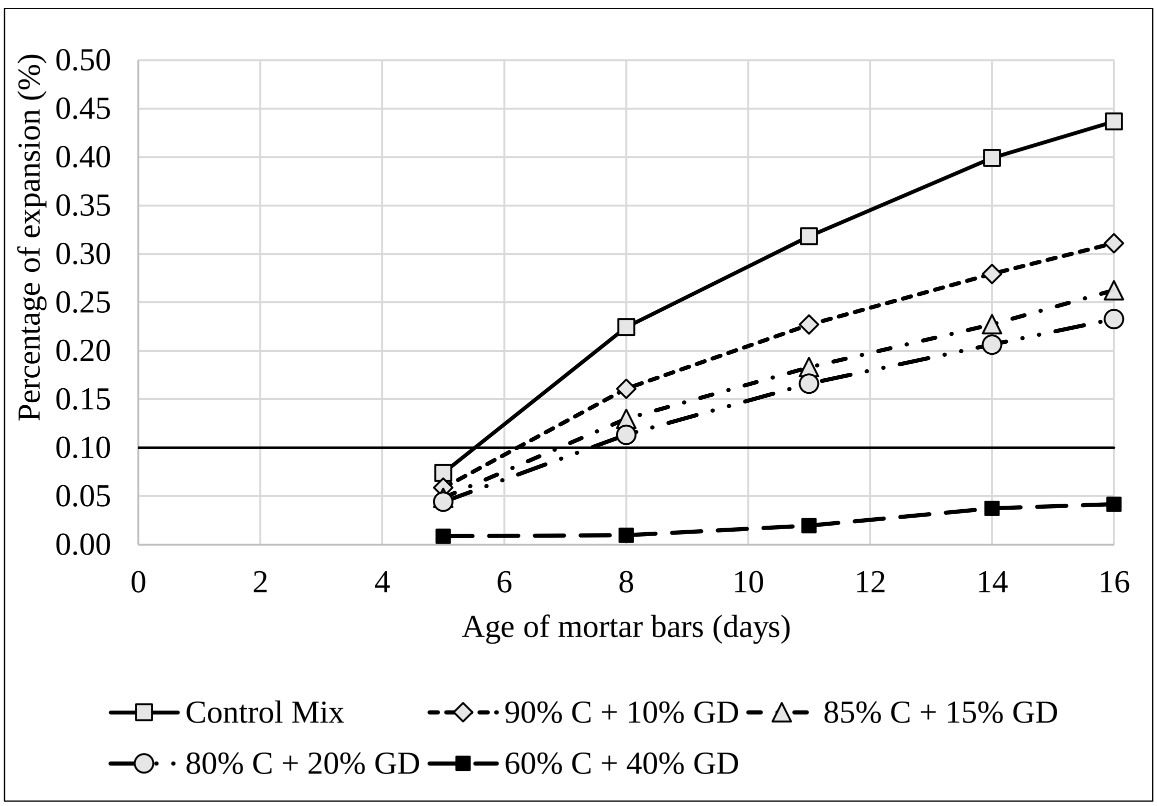

Figure 3-2 Average expansion for all mixtures containing glass dust; 4 replicates each.

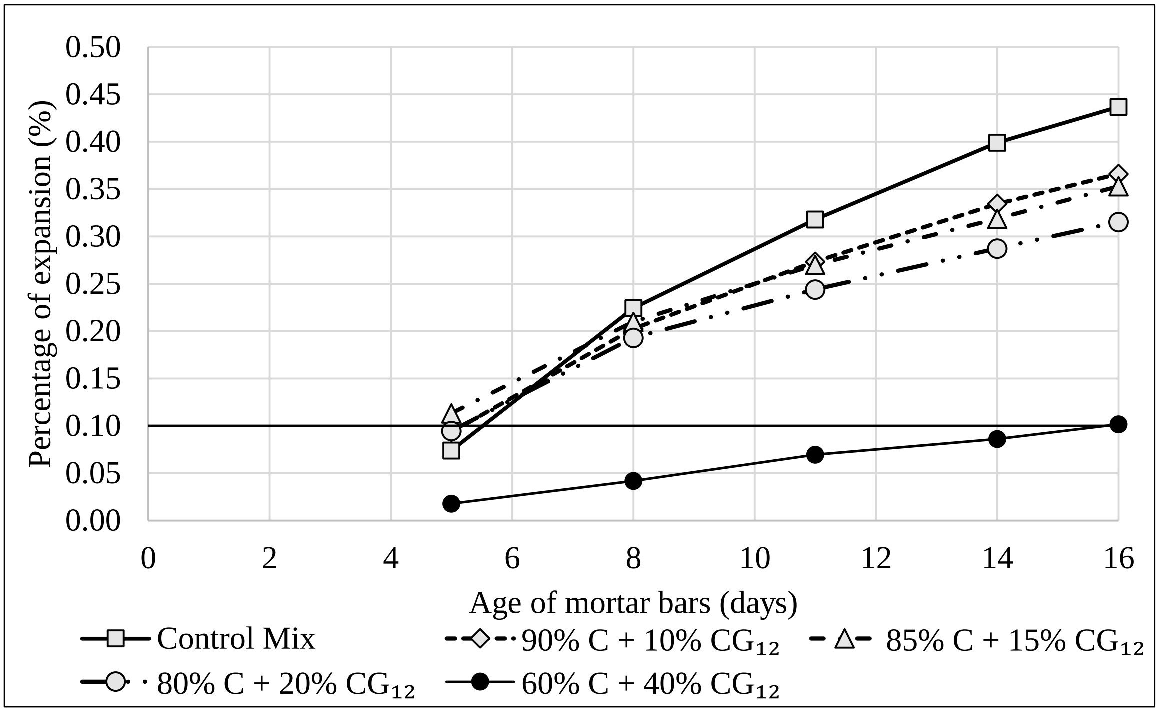

Figure 3-3 Average expansion for all mixtures containing CG_{12}; 4 replicates each.

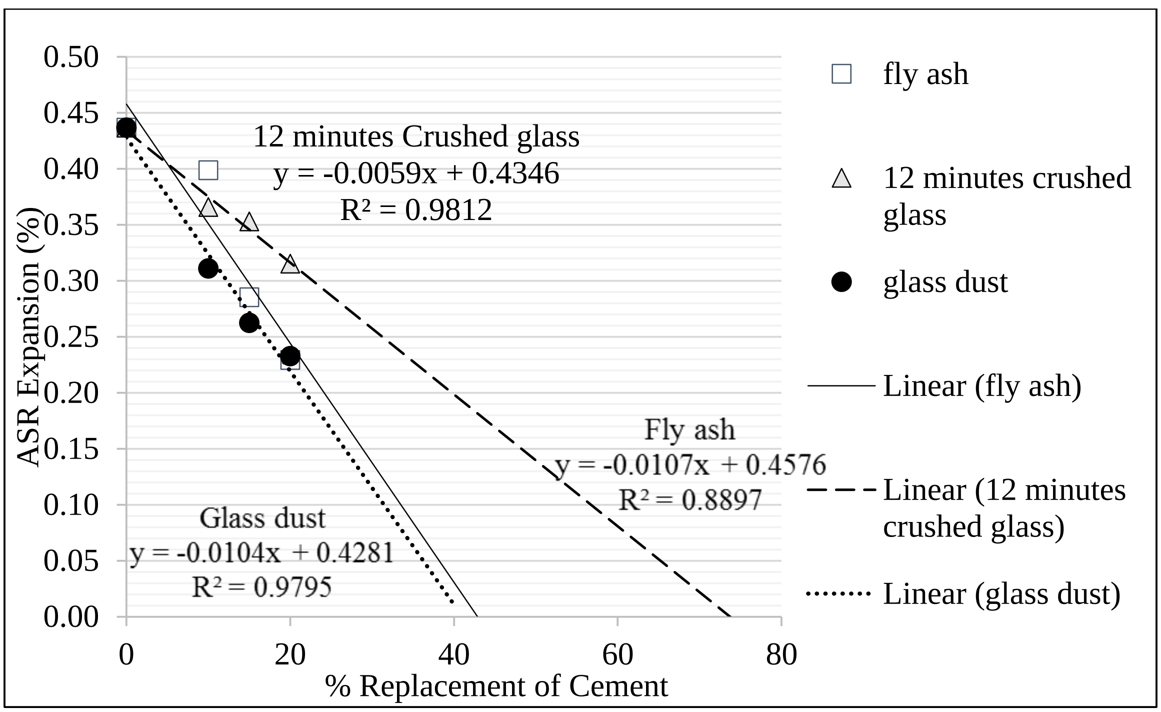

Figure 3-4 Regression expansion curve of glass dust, crushed glass, and fly ash based on up to 20% replacement of cement by weight. Linearly extrapolated to predict possible % replacement of cement needed to be below ASR limit of 0.10%.

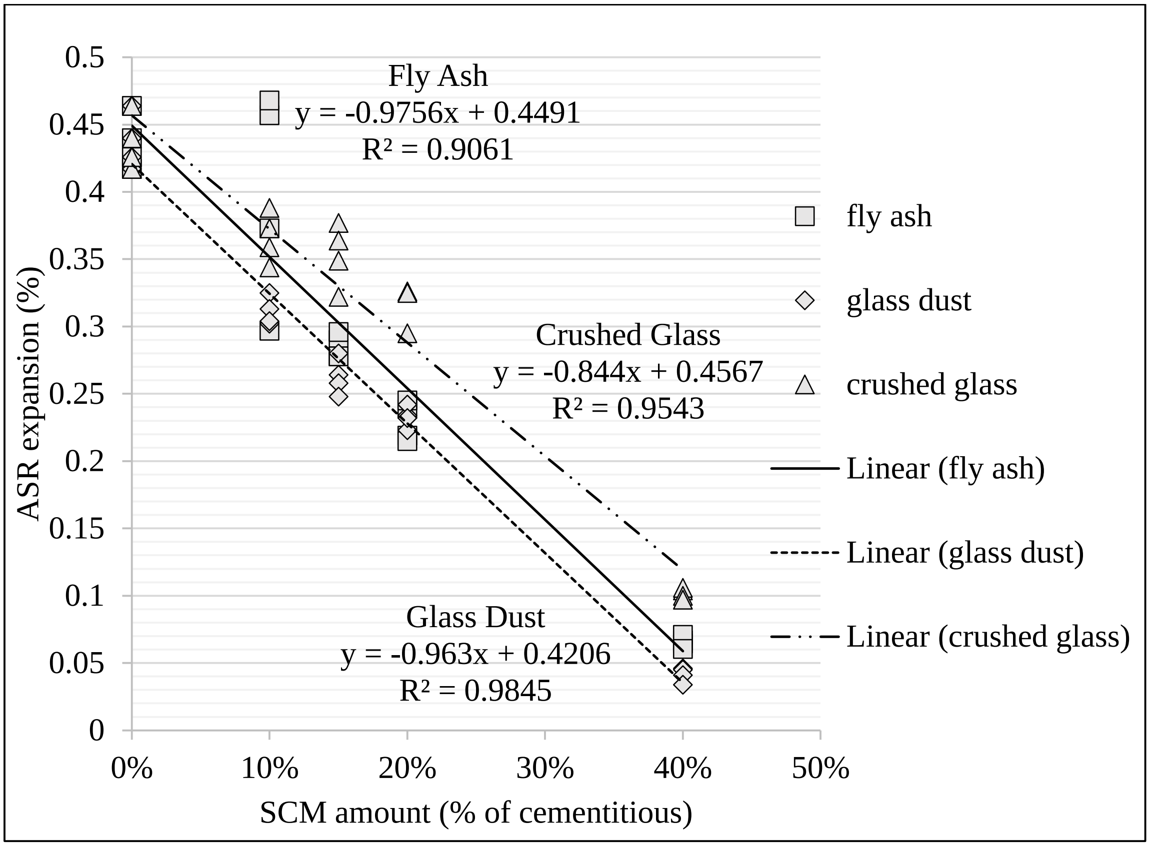

Figure 3-5 Updated regression expansion curve of glass dust, crushed glass, and fly ash including 40% replacement of cement by weight.

This updated regression analysis indicates that the fly ash and glass dust are similar and would need a minimum of 35% of replacement of cement in this specific mortar test to be below the 0.1% limit of expansion. Crushed glass, even at 40% replacement, shows an expansion limit slightly more than the acceptable limit.

3.1.2. Comparison to other SCMs

At 15% replacement of cement, different types of supplementary cementitious materials were compared for their ASR resistance for an average of 4-mortar replicates, as shown in Figure 3-6. The lowest expansion was for 15% ultra-fine pumice at 0.01% expansion by 14 days of immersion.

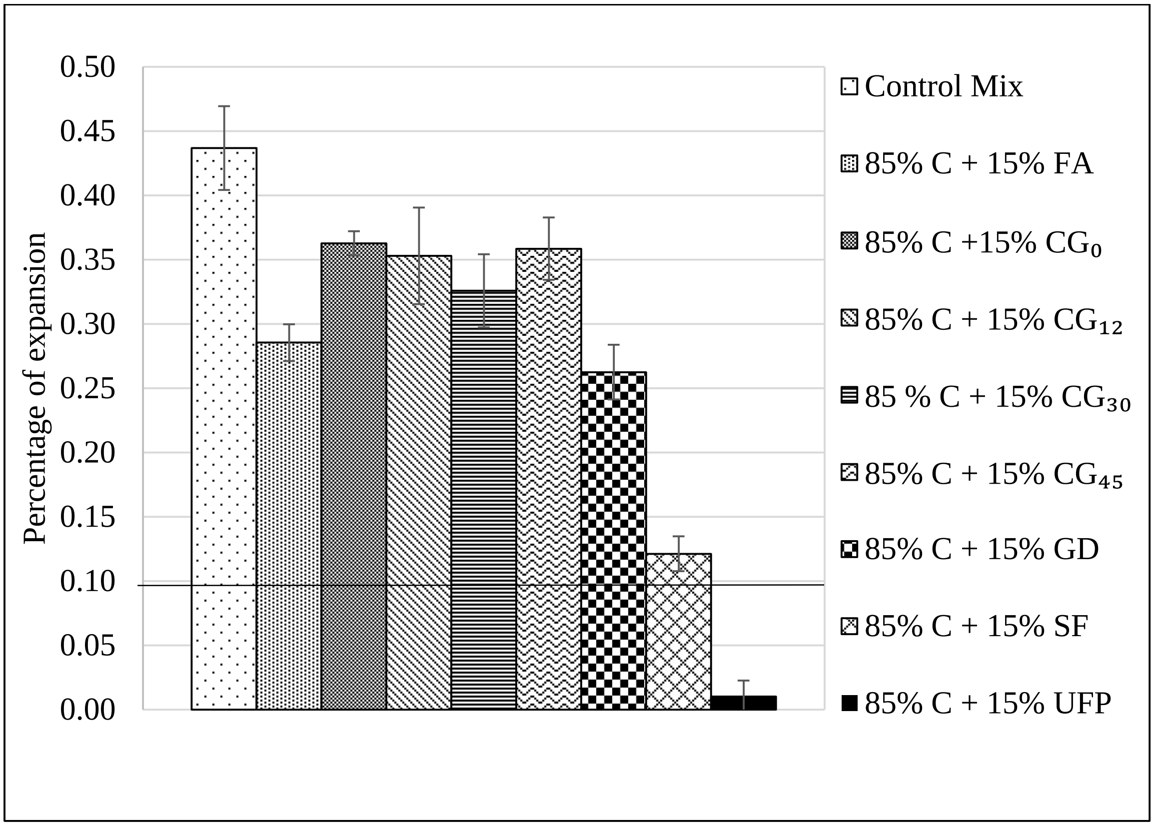

Figure 3-6 Average expansion after 16 days for all tested mixtures with 15% replacement of cement; 4 replicates each.

The low ASR expansion with the pumice verifies previous research [22] claiming that this type of pumice has very high resistance to ASR. A surprising result is that the silica fume at 15% replacement did not fall under the 0.1% ASR expansion limit despite its finer particle size and more reputable pozzalonic behavior.

3.1.3. Crushing time

It was hypothesized that finer glass particle sizes would result in more resistance to ASR expansion. Since it was previously determined that the crushing time is not directly correlated with particle size, the CG_0, which has the largest average particle size of the glass, had slightly larger ASR expansion than CG_{45}, which had the lowest average particle size. Since there is little difference in particle size between the 12, 30 and 45 minutes crushed glass, no trend on particle size versus ASR resistance could be stated at this time.

3.1.4. Combinations of fly ash with glass

The ASR expansion of blended combinations with 15% glass and 15% fly ash, creating a total of 30% SCM are shown in Figure 3-7. The mixture combination of the glass dust and fly ash did fall slightly below the 0.1% ASR expansion limit. Yet, the combination of FA and CG_{12} expands by 0.02% more than the acceptable limits.

A plot of the expansion with time for 40% blended SCMs of fly ash and glass is shown in Figure 3-8. This confirms that except for mix designs with mixed-color crushed glass at 40% and cement at 60%, all the other mixtures with 60% cement and 40% SCM had low expansion that met the ASTM limit. This may be due to the reduced cement content or the effectiveness of the fly ash and glass combination.

3.1.5. Minimum SCM dosage for ASR

As previously stated, the mix designs with 40% glass dust, and fly ash all had ASR expansion below the acceptable limit, 0.1%, and show almost equal percentage of expansion after 14 days submerged in a sodium hydroxide solution. This is illustrated in comparison with other mixtures, which also expanded below the ASTM limit seen in Figure 3-9. This illustrates that UFP at 15% replacement of cement shows the lowest ASR expansion. Some mixtures with 30% SCM combination, such as the 15% of GD and 15% of FA combination also were below the limit. It is unknown at this time whether the 0.04% variation in expansion might be caused because of the 5% increase in fly ash resisting more ASR, or whether the 5% increase in glass dust is more resistive to ASR as a SCM.

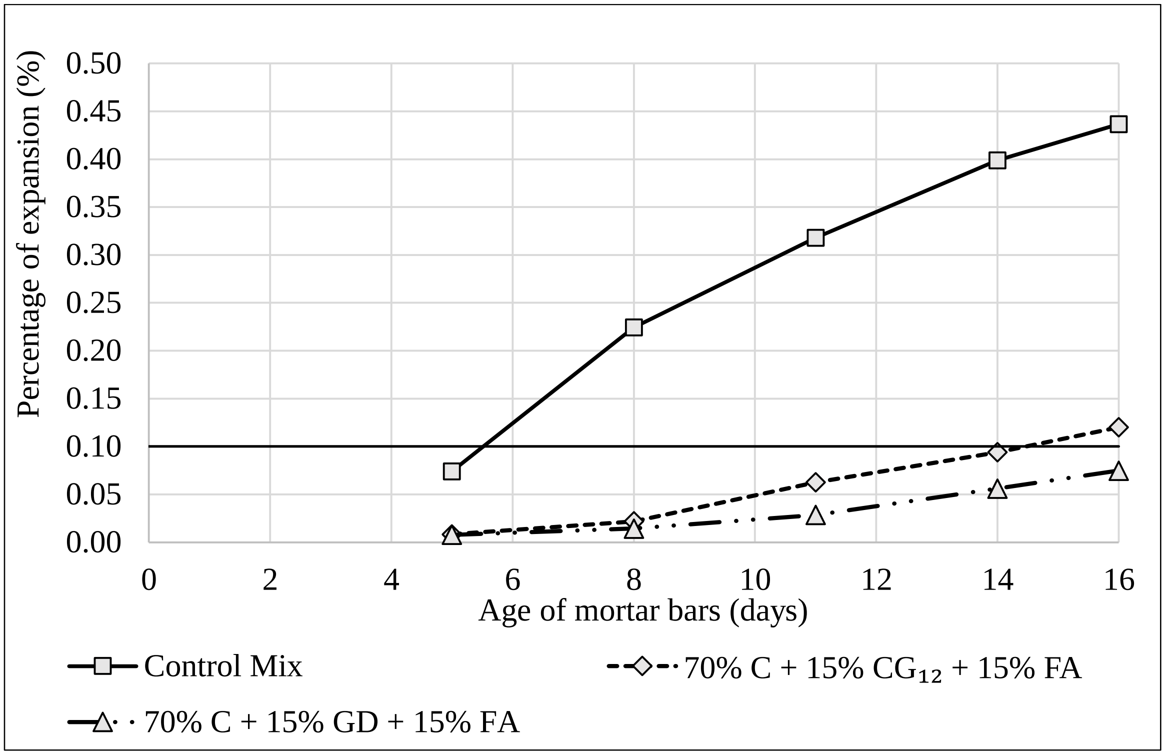

Figure 3-7 Average expansion of mix designs with 30% replacement of combined fly ash and glass as a SCM; 4 replicates each.

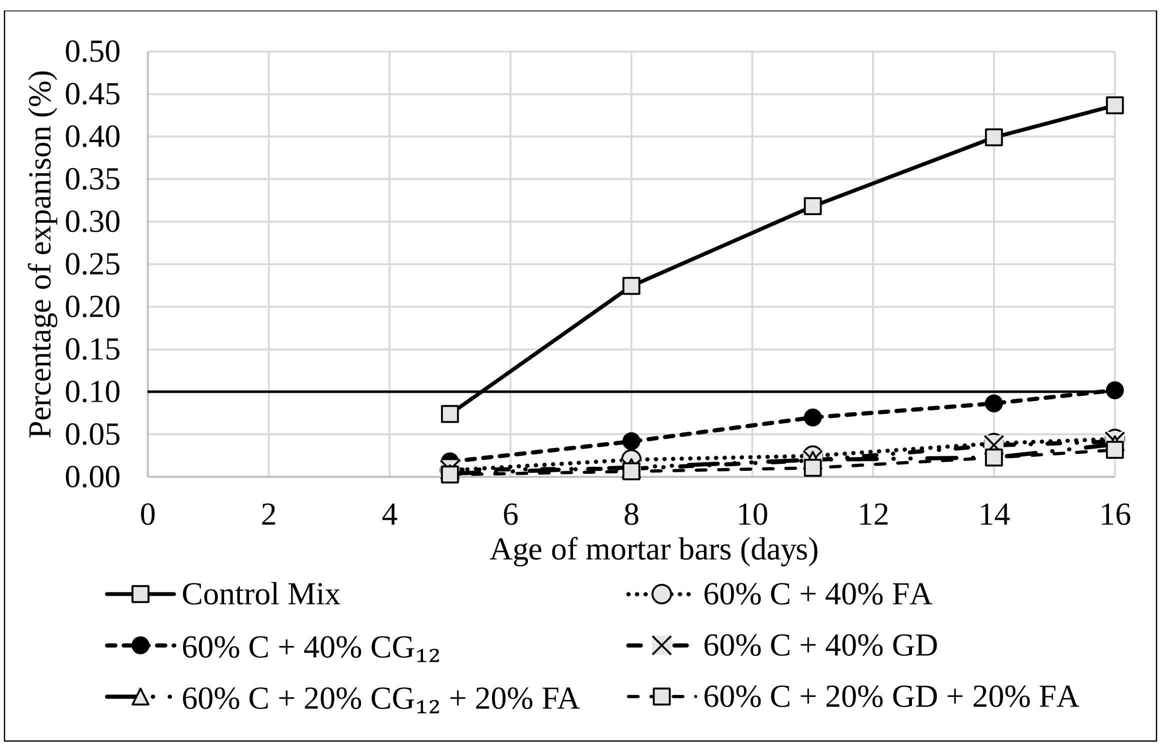

Figure 3-8 Average expansion of mix designs with 40% replacement of combined fly ash and glass as a SCM; 4 replicates each.

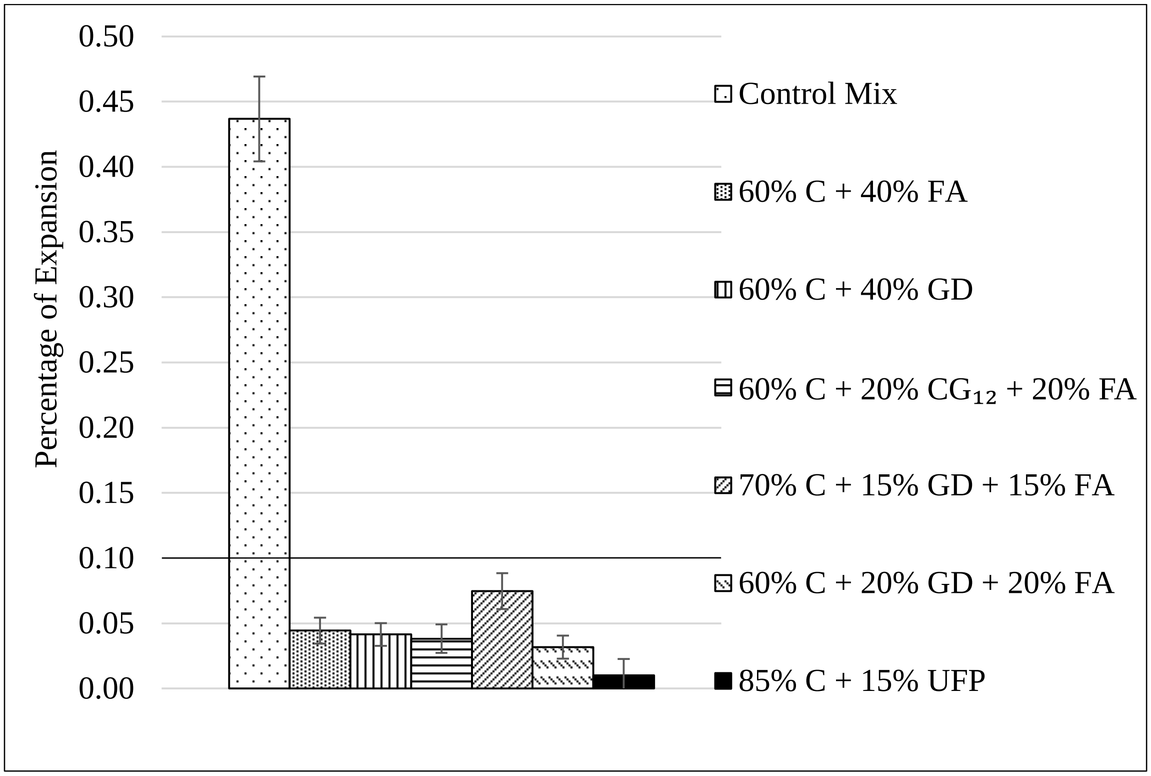

Figure 3-9 Average expansion after 16 days for all tested mixtures that fall under the 0.10% limit compared to the control mix; 4 replicates each.

The reduction in ASR could be occurring either from the specific SCM or possibly from the reduced cement content of 60%-70%, and thus the reduced amount of free calcium often necessary to have ASR expansion occur.

3.2. Compressive Mortar Cube Strength

The compressive strengths of each mortar mix at 28 and 91 days is shown in Table 3.2 and at 3 and 7 days is shown in Table 3.3. The coefficient of variation (COV) for all the mortar mixes at 3, 7, 28, and 91 days of age was low except for that of the 15% fly ash at 7 days of age and the 100% cement at the age of 28 days. All mixtures containing glass, whether it was crushed or collected dust demonstrated a decrease in the compressive strength at all ages, when compared to the control mix mortar.

Table 3.2 Statistics on the Measured Mortar Compressive Strengths at 28 and 91 days

Mix Design	28-day			91-day		
Percentage replacement by weight	Ave (psi)	Std Dev (psi)	COV (%)	Ave (psi)	Std Dev (psi)	COV (%)
Control Mix	5309	169	3*	6201	303	5
90% C + 10% FA	5246	325	6	6581	561	2*
85% C + 15% FA	5881	144	2	6705	435	6
80% C + 20% FA	4298	246	6	5529	359	6
90% C + 10% CG_{12}	4157	40	1	5415	94	2
85% C + 15% CG_{12}	4116	190	5	4923	245	5
80% C + 20% CG_{12}	3741	443	1*	4447	125	3
90% C + 10% GD	3671	166	5	4592	296	6
85 % C + 15% GD	3697	142	4	4556	380	5*
80% C + 20% GD	3164	183	6	4243	178	4
80% C + 10% CG_{12} + 10% FA	4229	398	6*	5167	548	5*
70% C + 15% CG_{12} + 15% FA	4148	289	7	5877	103	2
60% C + 20% CG_{12} + 20% FA	2578	111	4	3913	80	2
80% C + 10% GD + 10% FA	3819	263	7	5113	189	4
70% C + 15% GD + 15% FA	2796	174	6	4392	229	5

*COV counted for only 2 replicates. All other mixture samples based on 3 replicates.

According to ASTM [31] the maximum coefficient of variation (COV) for any age should be ≤ 8.7% for 3 samples and ≤ 7.6% for 2 samples. The mortar mixtures that showed a COV greater than 8.7% for 3 replicates were adjusted by dropping the outlier and only comparing the remaining 2 replicates to verify whether the updated COV falls below ≤ 7.6%. All mortar mixtures, either with 2 replicates or 3 replicates, fell below the COV percentages mentioned in ASTM standards except the mortar mixture with 15% fly ash as a SCM at 7-days.

Table 3.3 Statistics on the Measured Mortar Compressive Strengths at 3 and 7 days

Mix Design	3-day			7-day		
Percentage replacement by weight	Ave (psi)	Std Dev (psi)	COV (%)	Ave (psi)	Std Dev (psi)	COV (%)
Control Mix	3176	80	3	4056	17	0.4
90% C + 10% FA	3079	158	5	4036	467	6*
85% C + 15% FA	3166	125	4	3940	620	11*
80% C + 20% FA	2099	180	1*	2822	156	6
85% C + 15% CG_0	1930	79	4	2455	66	3
90% C + 10% CG_{12}	2476	36	1	2981	158	5
85% C + 15% CG_{12}	2205	255	5*	2972	148	5
80% C + 20% CG_{12}	1995	72	4	2562	131	5
85% C + 15% CG_{30}	2199	96	4	2717	155	6
85% C + 15% CG_{45}	2547	134	5	3106	238	8
90% C + 10% GD	2191	184	8	2757	352	3*
85% C + 15% GD	1989	85	4	2639	47	2
80% C + 20% GD	1839	51	3	2301	53	2
60% C + 40% GD	1293	59	5	1526	49	3
80% C + 10% CG_{12} + 10% FA	2171	224	4*	2904	112	4
70% C + 15% CG_{12} + 15% FA	2165	257	1*	2721	262	5*
60% C + 20% CG_{12} + 20% FA	1410	59	4	1721	52	3
80% C + 10% GD + 10% FA	2078	216	6*	2664	9	0.35
70% C + 15% GD + 15% FA	1598	79	5	2234	148	7

*COV counted for only 2 replicates. All other mixture samples based on 3 replicates.

The higher variation in the strength results for this mortar mixture with 15% fly ash at 7-days was expected to be related to a mechanical error of the loading machine of that particular day.

3.2.1. Effect of fly ash on strength

Strength gain results with mixtures containing only fly ash are shown in Figure 3-10. It was expected that increasing the amount of fly ash would increase the strength of the mortar, especially at the later ages of 28 and 91 days. For the mixtures tested in this research, the mixtures with 20% fly ash were always lower in strength regardless of age. Other mixtures at 10% and 15% FA as a SCM had negligible effect on strength except at the later ages. There appeared to be a long-term strength-based optimum FA content of 15% in this study.

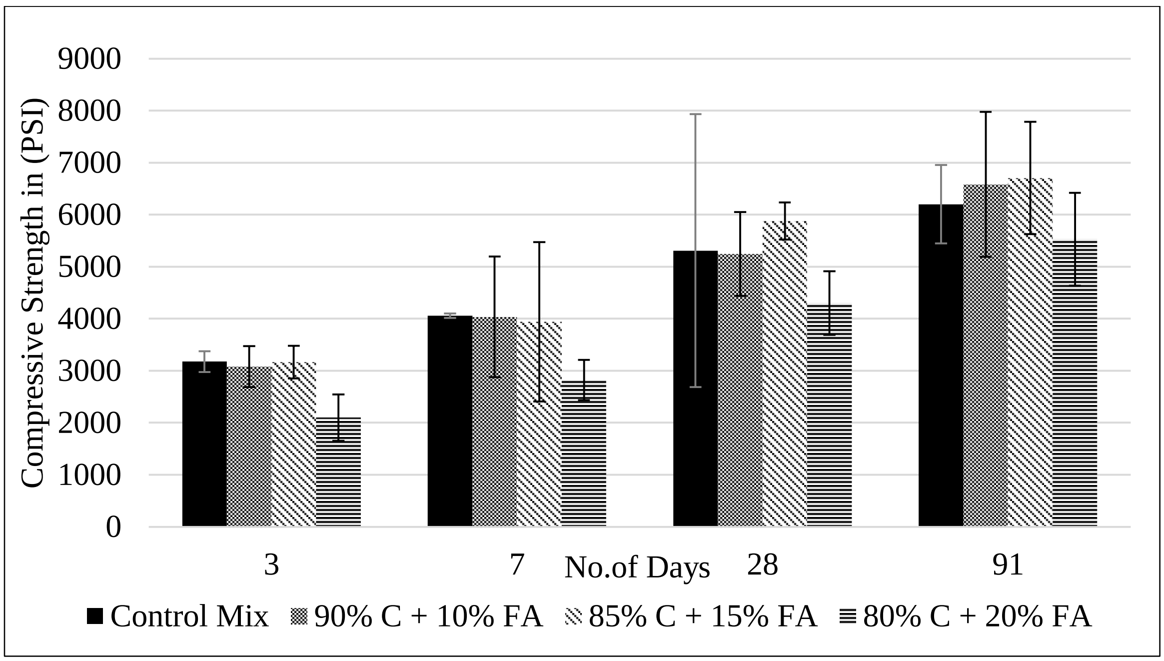

Figure 3-10 Mortar cube compressive strength comparison of different ages for mix designs with different percent replacement of fly ash. Average of 3 and 95% confidence interval shown.

3.2.2. Effect of glass dust on strength

Figure 3-11 shows the compressive strength of mortar cubes at 3, 7, 28 and 91 days of ages with different percent replacement of GD, and in combination with FA as a SCM, compared to the control mix.

As stated previously, all mixtures containing glass powder showed lower strengths than the control mix. The 91 days of age mix design containing 15% FA and 15% GD showed the lowest strength with reduction in strength of 29.2% compared to the control mix. GD at 40% cement replacement by weight shows the least strength at 3 and 7 days of age compared to all other glass or cementitious mixes.

3.2.3. Effect of crushed glass on strength

Figure 3-12 shows the compressive strength of mortar cubes at 3, 7, 28 and 91 days of age with different percent replacement of CG_{12} and in combination with FA. The mix design containing 20% FA and 20% CG_{12} shows the lowest strength at all ages, with reduction in strength of 37% compared to the control mix irrespective of increasing in strength by 52% from the age of 28 to 91 days. The mixture with 15% FA and 15% of CG_{12} had a 42% increase in strength from 28 to 91 days of age, and showed 91-day strengths closest to the control mix.

Glass with additional crushing times of 30 and 45 minutes and at 15% cement replacement are shown in the Figure 3-13. With a reduction in particle size, strength increased but not with much variation in strength seen from CG_0 to CG_{45}. As particle size of CG_{30} is higher than CG_{12} and CG_{45}, it shows low strength.

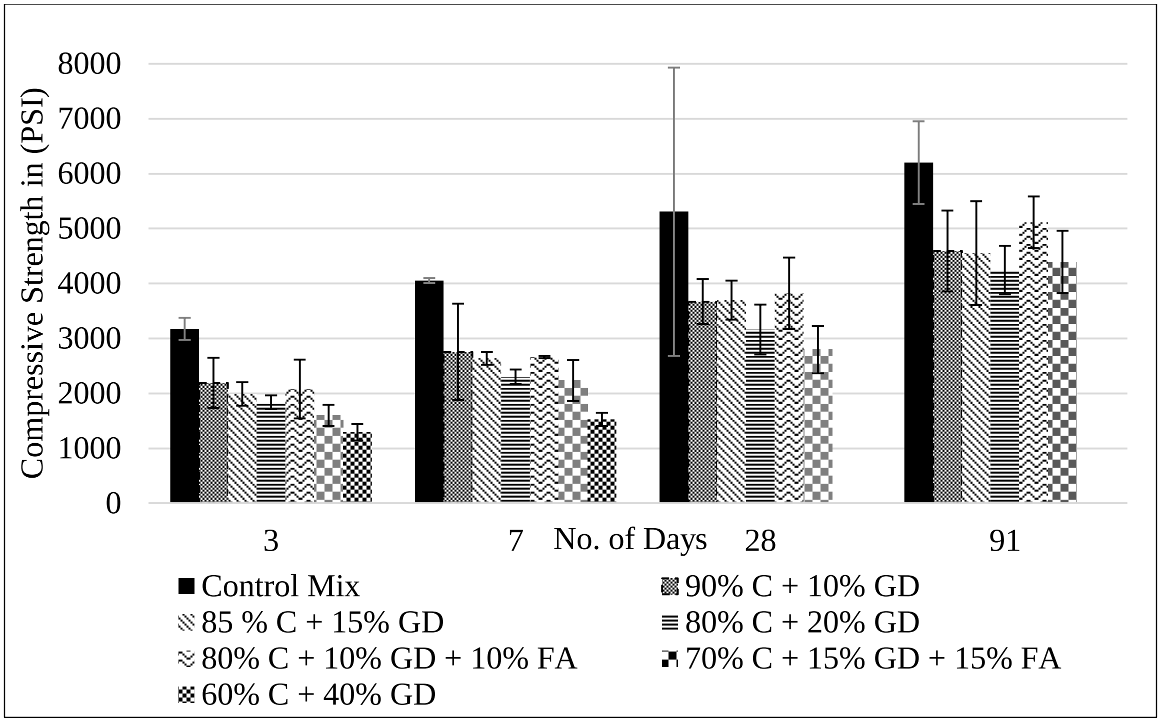

Figure 3-11 Mortar cube compressive strength comparison of different ages for mix designs with clear- and green-colored glass dust and fly ash. Average of 3 and 95% confidence interval shown.

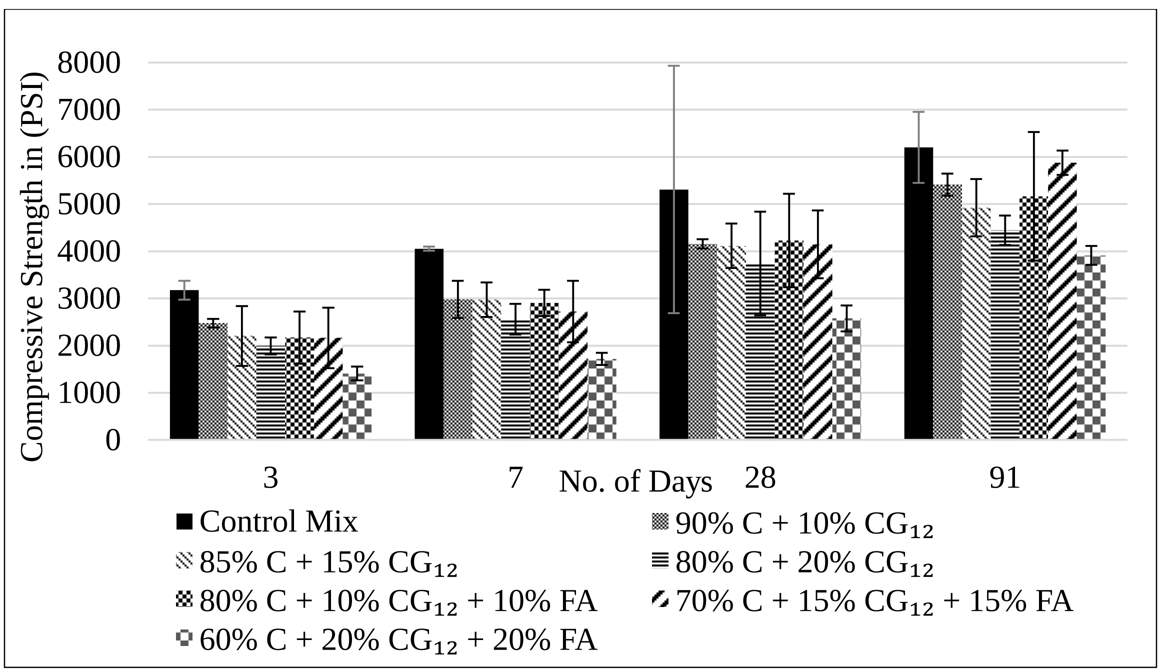

Figure 3-12 Mortar cube compressive strength comparison of different ages for mix designs mixed-colored crushed glass and fly ash. Average of 3 and 95% confidence interval shown.

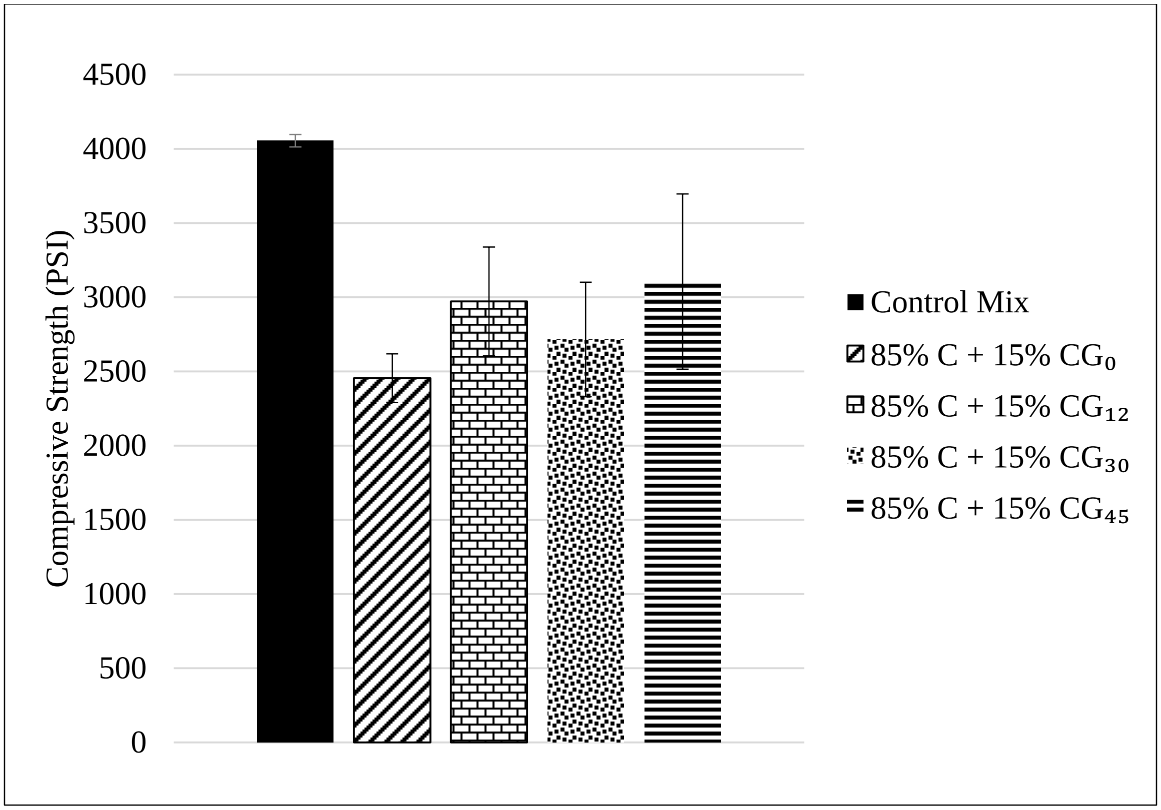

Figure 3-13 Seven-day mortar cube compressive strength comparison of mixed colored crushed glass crushed for different timings. Average of 3 and 95% confidence interval shown.

3.2.4. Comparing SCM content vs strength

A general comparison of each of these mixtures with glass or fly ash are compared, as shown in Figure 3-14 for 91 day compressive strengths. Out of all mix designs 15% FA as a SCM shows the highest strength at 91 days. The combination of 20% FA with 20% CG_{12} shows the lowest strength at 91 days of age. The compressive strength does not vary significantly between 10% and 15% replacement of glass, whether that be CG or GD as a SCM. At 20% SCM with the combination of FA, CG_{12} and GD show approximately the same strength. The FA and CG_{12} at 30% total SCM was found to be ideal since it is closest at 95% of the average control mix strength.

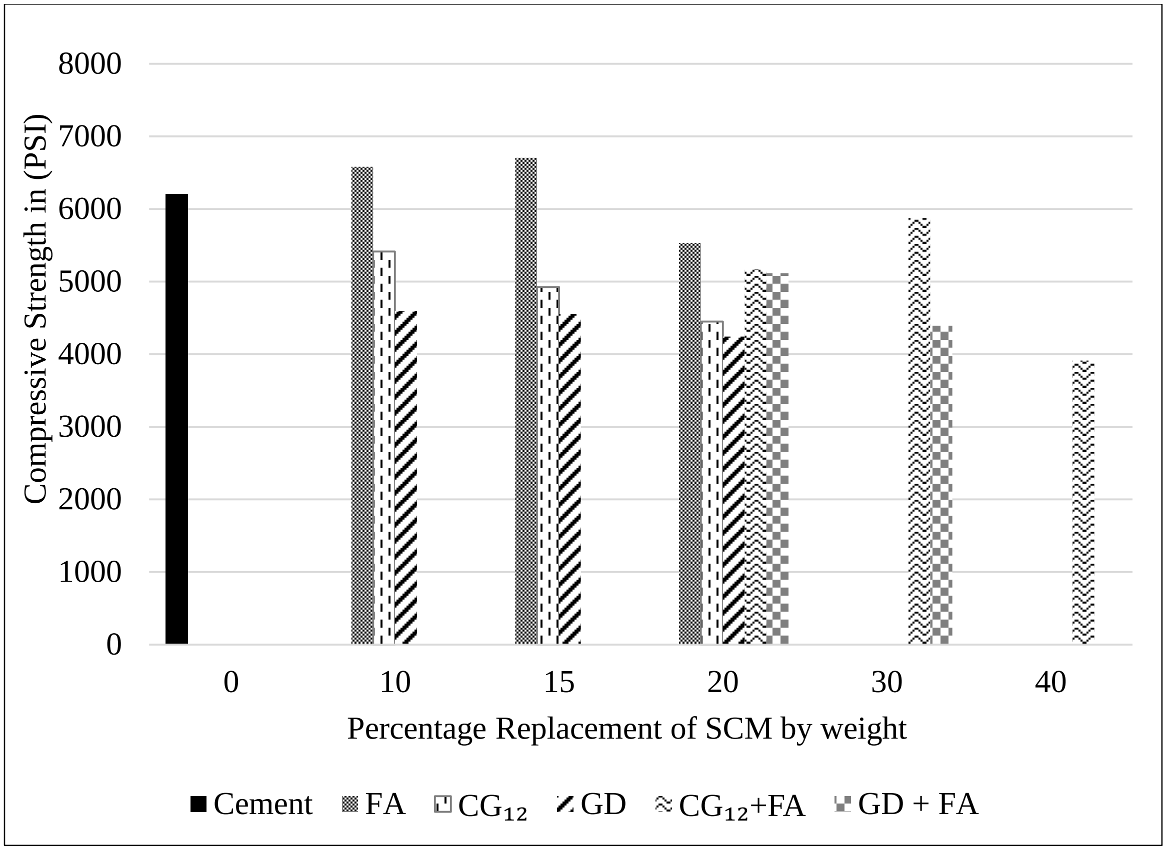

Figure 3-14 Average strengths at 91 days comparison of mix designs with varying total cementitious material replacement; 3 replicates of each.

CHAPTER 4

COST ANALYSIS

4.1 Introduction

As clear- and green-colored glass dust shows low ASR despite its low strength when replaced at 40% of cement, it is recommended to use clear- and green-colored glass dust as a SCM where strength is not a criteria. This again is from the collection of dust produced from normal crushing of the clear- and green-colored glass and does not require additional crushing methods. A cost analysis study was made to determine the feasibility of whether glass powder could provide a competitive low-ASR susceptible SCM for the ready-mix concrete market. This chapter aims to investigate both whether there is enough quantity of glass that can be produced to meet the demands of a construction industry in the state of Utah, and what might be the costs associated by using glass dust in a small project.

4.2 Comparison of Cement and Glass Dust

The expenses to the Momentum glass recycling company associated with collection, transportation to recycling plant, sorting out the clear- and green-colored glass, steaming to separate the food or other chemical contamination, and crushing of clear- and green-colored glass comes to approximately $60/ton [32]. As a comparison, Portland type

II cement costs over $105-$120/ton [33]. For glass dust to be used in the construction market, it would likely need to be transported and stock-piled at a ready-mixed concrete plant. This additional cost is anticipated to be 40% [33] compared to the cost of the collection, sorting and crushing expenses. The reduced net cost will affect the cost of the total concrete mix ordered. Basic economic theory indicates that if there is enough quantity of glass dust to satisfy the demands of the construction industry for specific projects, then the cost per ton of clear- and green-colored glass would go down.

4.3 Quantity Comparison

Only two plants (Holcim Company's Devil's Slide and Ash Grove Company's Nephi plant) in the state of Utah produce cement. Each cement plant produces approximately 750,000 metric tons of cement per year [34, 35].

The Momentum glass recycling plant is the only plant in the state of Utah that collects waste glass and crushes it. On average, the Momentum glass recycling plant currently processes approximately 360 metric tons of clear- and green-colored glass dust per year. This is calculated to be approximately 0.02% of cement produced each year in the state of Utah. This is significantly smaller than what the cement manufacturers would consider stock-piling and using in their raw feed towards new cement production. Alternatively, the waste glass could still be used in specific projects as a SCM in concrete or mortar mixtures.

Waste glass dust of clear- and green-colored glass could be used as a SCM in projects like sidewalks, driveways, curbs, and pavements where strength (typically around 5000-6000 psi) is not a major criteria yet durability matters [36, 37]. For example, a concrete without any SCM could be placed in a small driveway pavement of say 50ft in length x 20ft width x 0.5ft depth, or 18.52 cubic yards. If 40% of the cement in this concrete mix were replaced with glass dust, then the amount of glass dust needed for this small project would be 7.87% mass of the overall concrete mass used in this pavement for a mix design, as shown in Table 4.1. This comes out to be approximately 5741 lbs of glass dust for this concrete project.

4.4 Cost Comparison of Glass Dust with Cement and Other SCMs

One cubic yard of concrete costs $93 [38] without any SCM in it. For this example concrete driveway project, the concrete materials could cost $1,722 when no SCM is used in it.

Cost of concrete = cement + SCM + water + coarse aggregate + fine aggregate + fees

Cost of mortar = cement + SCM + water + fine aggregate + fees

Table 4.1 Mortar [31] and Concrete [39] Mix Design Used for Example Projects

		Mortar	Concrete
Cement	Lb/yd³	616.8	464
Glass Dust	Lb/yd³	411.2	310
Water	Lb/yd³	499	280
Coarse Aggregate	Lb/yd³	-	1851
Fine Aggregate	Lb/yd³	2828	1034
Total	Lb/yd³	4355	3939
Water Cement ratio		0.485	0.36

The cement component alone in concrete is about $41.02 to $46.44 per cubic yard of concrete. The cost of all potential cementitious components can be seen in Table 4.2. Pricing might vary based on quality, availability, and the number of sources in a geographical area. Glass dust is cost effective compared to silica fume and ultra-fine pumice. The price per ton of ultra-fine pumice is approximately 9.3 times higher than glass dust; while fly ash is approximately 0.3 to 0.8 times lower than the glass dust cost per ton. Transportation costs, shown in Table 4.2, are estimated to be 40% [33] of cost of overall volume of concrete or mortar used to complete the project. The transportation cost also depends on the distance from ready-mix plant to the site. These transportation costs were not included in the cost analysis numbers for this research.

If 40% of cement is replaced with glass dust, then the cementitious component in concrete for each cubic yard of concrete would be $33.89 to $37.14 per cubic yard of concrete. This would mean a savings of approximately $7.13 to $9.30 per cubic yard of concrete, or an overall project savings of approximately $132 or more.

Table 4.2 Cost Comparison of Glass Dust Compared to Cement and Other SCM

Materials	Cost per ton at ready-mix plants	Cost per ton with 40% extra for transportation
Cement	$105-$120	$147-$168
Glass Dust	$60	$84
Fly ash[33]	$20-$50	$28-$70
Silica Fume[33]	$700-$1000	$980-$1400
Ultra-Fine Pumice[40]	$560	$784

If the same project is constructed by using a mortar mix, then the savings will be greater. The cement component alone in the mortar is about $54.48 to $61.68 per cubic yard of mortar. If 40% of cement is replaced with glass dust, then the amount of glass dust needed for this small project would be 9.44% mass of the overall mortar used in this pavement project. A cubic yard of mortar with 40% glass dust would cost approximately $45.03 to $49.34. The savings for mortar mixtures with the glass replacement would be $9.46 to $12.34 per cubic yard of mortar. For an equivalent project volume this would be about $175 of savings or more.

4.5 Summary

- Glass dust production is approximately 0.02% by weight of the total cement material demand produced each year for Utah.
- Cement costs approximately 1.75-2 times more than glass dust by weight.
- Glass dust is significantly cheaper than the other SCMs like silica fume and ultra-fine pumice, but slightly more expensive than fly ash.
- Approximately 7%-9% mass of glass dust can be incorporated in a ready-mix concrete batch to have the minimum ASR resistance as estimated by this study.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

Type II cement and moderately-reactive local sand causes ASR. Using glass powder as a supplementary cementitious material would reduce ASR. This research found the influence on the ASR expansion and compressive strength properties of using waste glass as a fine powder and added as a supplementary cementitious material in mortar. Mortar mixtures were created containing either mixed-colored glass that was crushed to a fine powder, clear- and green-colored glass dust, or in combination with a Class F fly ash. The general trends found were that 10-40% replacement of cement with crushed glass or glass dust resulted in reduced ASR expansion and reduced compressive strength compared to 100% cement. Some additional key findings are summarized as follows:

1. ASR was reduced to below the 0.1% limit of the accelerated ASR mortar expansion test for all mixtures containing 40% of either glass dust, fly ash, or combinations of these SCMs. Crushed glass powder shows 0.00175% higher expansion than the acceptable limit with a range of 0.0954 - 0.1081% expansion at 95% confidence interval. A mixture containing 30% of combined glass dust and fly ash also fell below the 0.1% limit of the ASR expansion test.

2. Mortar mixtures with clear- and green-colored glass dust were found to exhibit more resistance to ASR compared to that with crushed mixed-colored glass.
3. Mortar mixtures with clear- and green-colored glass dust had the lowest strength compared to that with mixed-colored crushed glass.
4. The use of fly ash at 10-15% cement replacement was found to increase the mortar strength after 28 days compared to the 100% cement.
5. An ultra-fine pumice (studied only at 15% replacement of cement) demonstrated the significantly lowest ASR expansion compared to all other mortar mix designs studied in this research.
6. Any additional crushing time beyond 12 minutes using the laboratory vibratory cup pulverizer was not found to significantly change the particle size.
7. Larger average particle sizes were found to have reduced measured strengths in the mortar mixtures containing crushed glass. Strength comparisons of the mixed-colored glass at 15% replacement were greatest, with an average particle size of 40 μm (CG_{45}) > 42 μm (CG_{12}) > 53 μm (CG_{30}) > 180 μm (CG_{0}). No significant ASR expansion difference is seen between the different crushed levels of glass; all are within the same confidence interval range of each other.
8. Overall, the cost analysis indicated that the glass dust, although useful for reduced ASR at 40% cement replacement, is not currently made in a large enough volume to be demanded or regularly stockpiled at most ready-mixed concrete plants. With a significant reduction in strength, it might only be useful as a supplementary cementitious material for curbs, sidewalks, or concrete pavements where compressive strength does not need to be over 6000 psi.

5.2. Recommendations

- As an ASR-resistant SCM, glass dust, at possibly 40% replacement of cement, may still be useful to the construction industry. Although some additional SCMs or chemical admixtures may be needed to improve the strength of the mixtures containing glass dust powder.
- The current quantity of clear- and green-colored glass dust produced by the Momentum recycling plant does not meet a possibly high demand from the construction industry.
- As not much quantity of glass dust is made for large project demands, waste glass recycling plants could sell the glass dust for smaller construction projects.
- Home-owners, small businesses, and city municipalities could encourage the ready-mix concrete plants to incorporate waste glass dust in their concrete for drive ways, sidewalks and curbs where a reduction in strength is not a major problem.
- In these smaller projects, durability against ASR is expected to be improved through the use of glass dust as a SCM in concrete.

5.3. Future Work Suggestions

- Mortar mix designs showing lower expansion of ASR in this research can be tested on concrete specimens using low and high reactive aggregates.
- The compressive strength results can be studied for higher ages (365 days) with the mix designs of 30 and 40% GD replacement of cement. A long-term age strength test can also be done with the combination of FA with GD, since these mortar mix designs were showing a higher percentage increase in strength from 28-91 days.

- Energy consumption during the process of crushing down the mixed colored waste glass from the particle size of 210 micron to 20 micron minus can be studied.
- A study on the effect of agglomeration of the glass particles based on type, process and time of crushing would be beneficial to continue further research.

APPENDIX

STRENGTH AND EXPANSION OF MORTAR WITH SCM

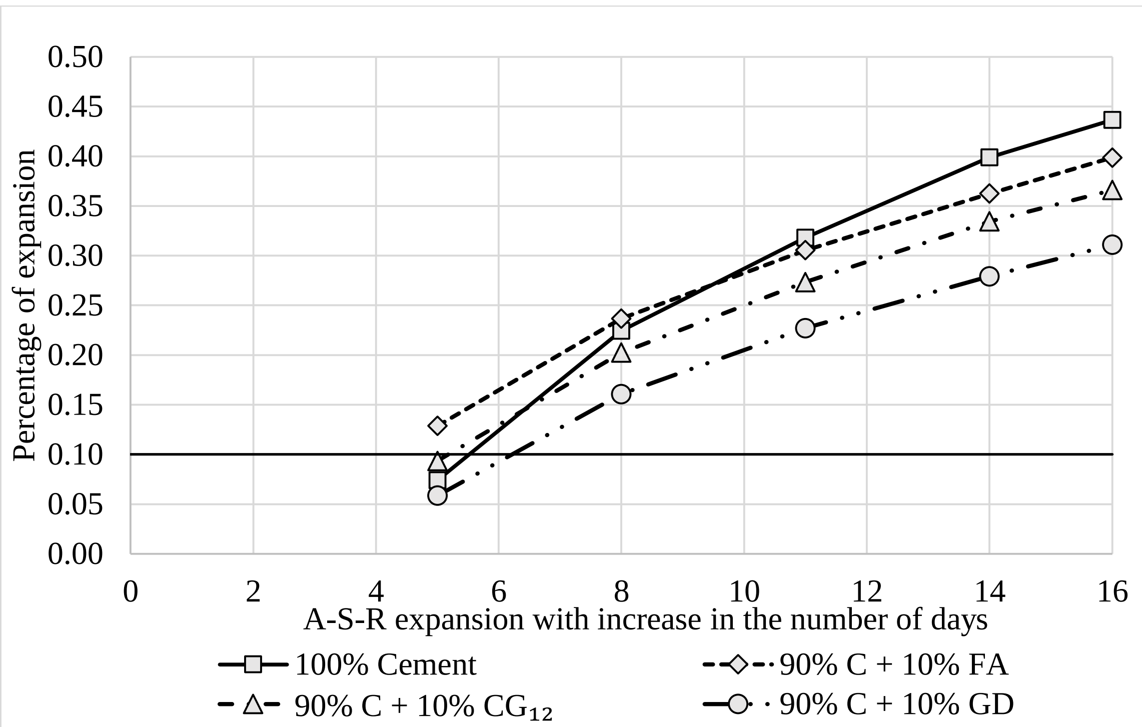

Figure A.1 Average expansion of different mix designs with 10% SCM compared to 100% cement; 4 replicates tested.

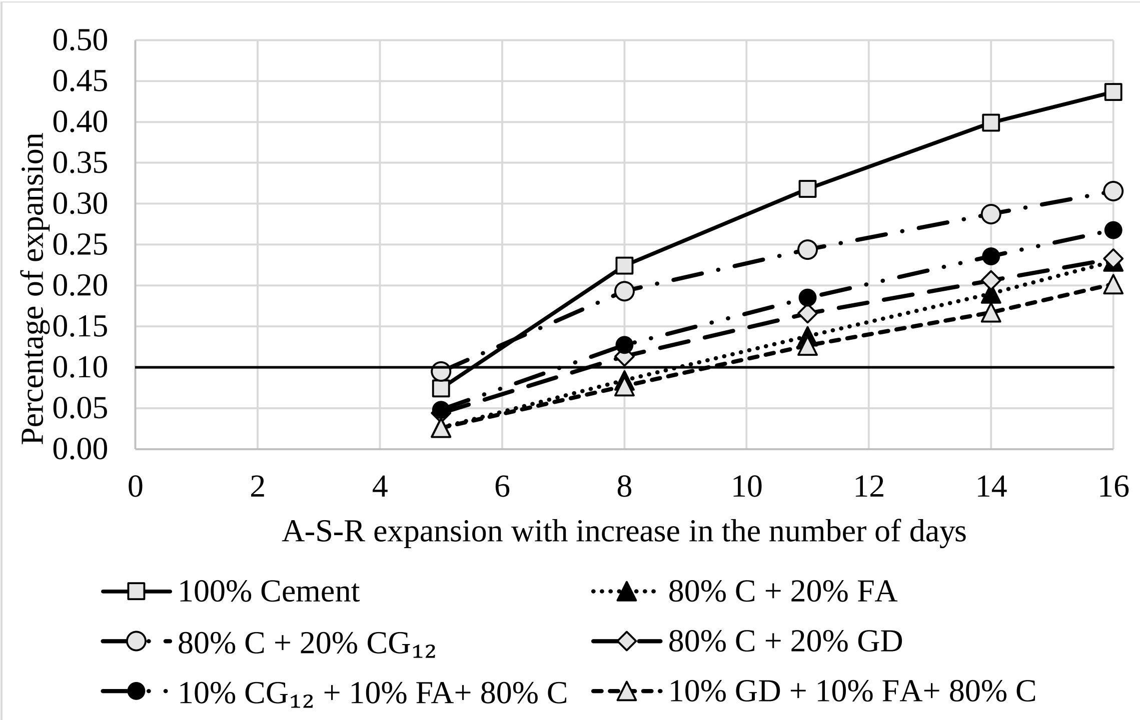

Figure A.2 Average expansion of different mix designs with 20% SCM compared to 100% cement; 4 replicates tested.

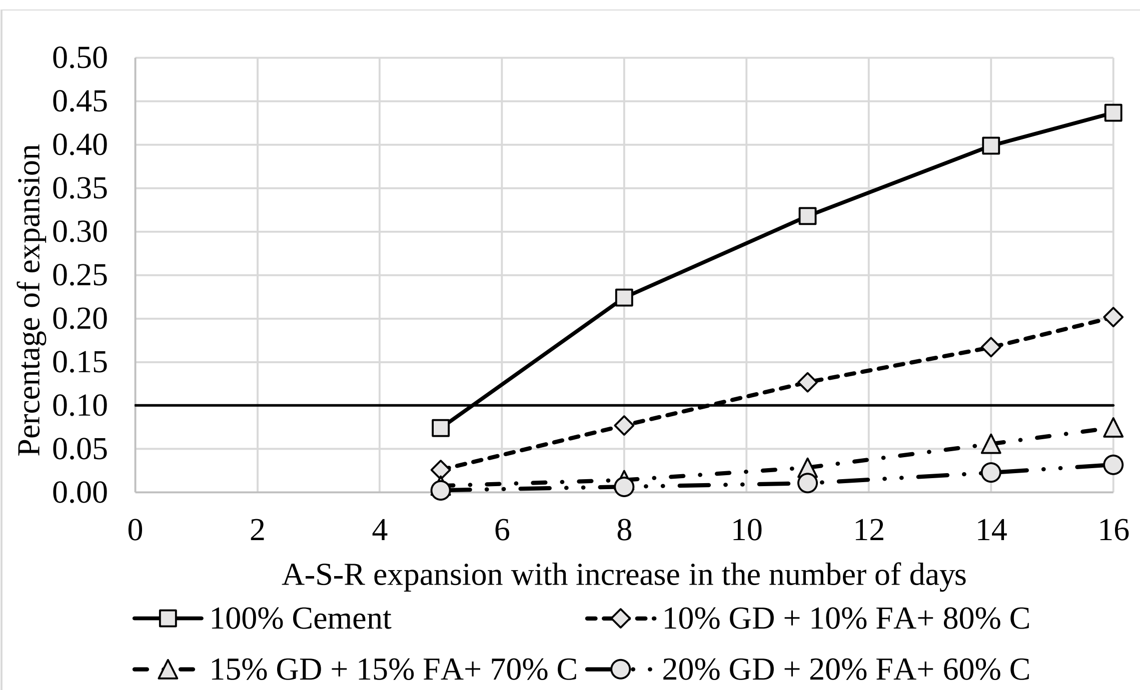

Figure A.3 Average expansion of mix designs with percentage variation of FA and GD as a SCM compared to 100% cement; 4 replicates tested.

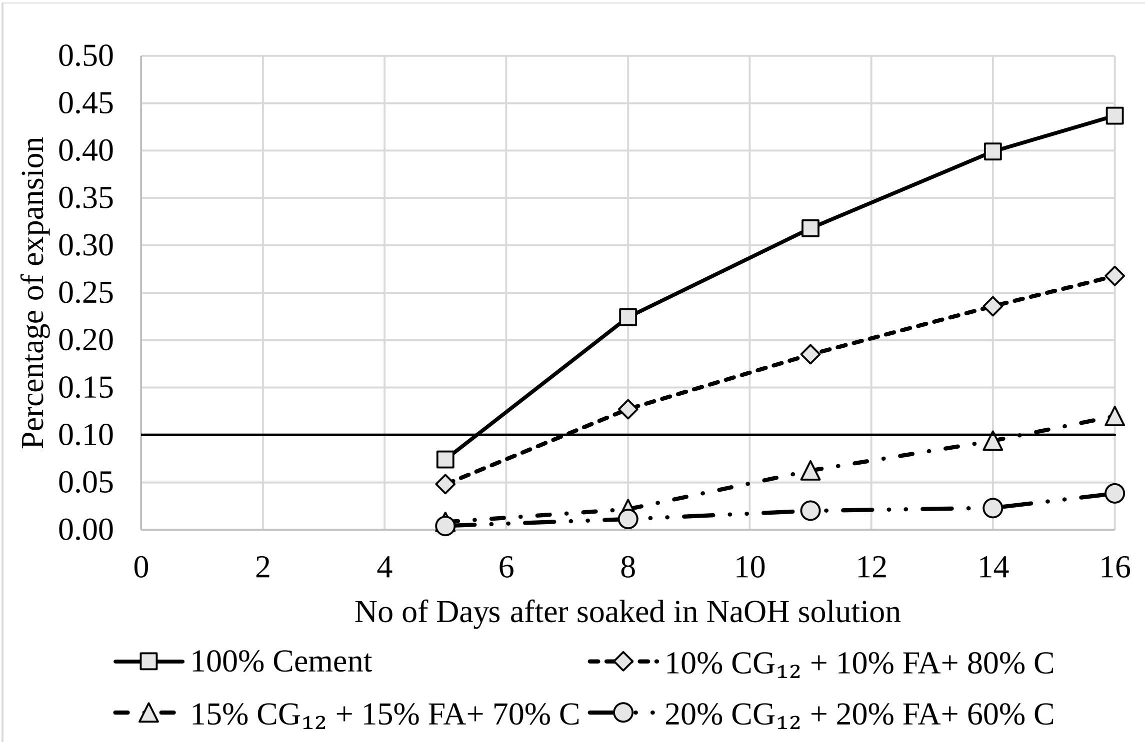

Figure A.4 Average expansion of mix designs with percentage variation of FA and CG_{12} as a SCM compared to 100% cement; 4 replicates tested.

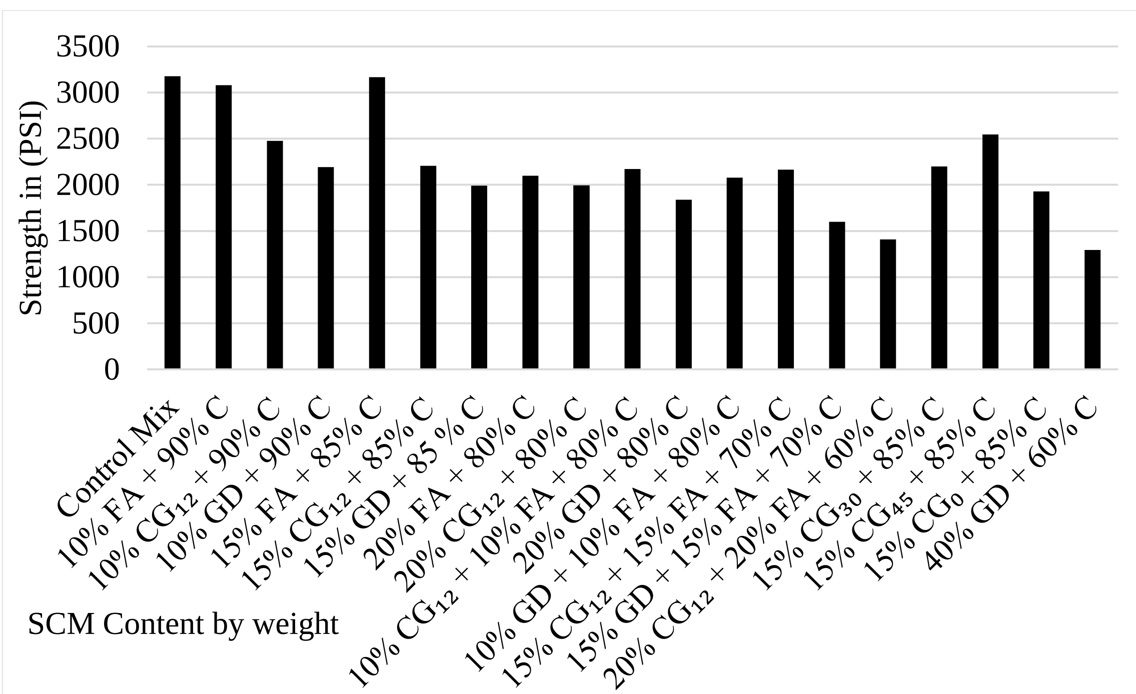

Figure A.5 Average 3-day mortar cube compressive strength of mix designs with different percent replacement of SCM; 3 replicates tested.

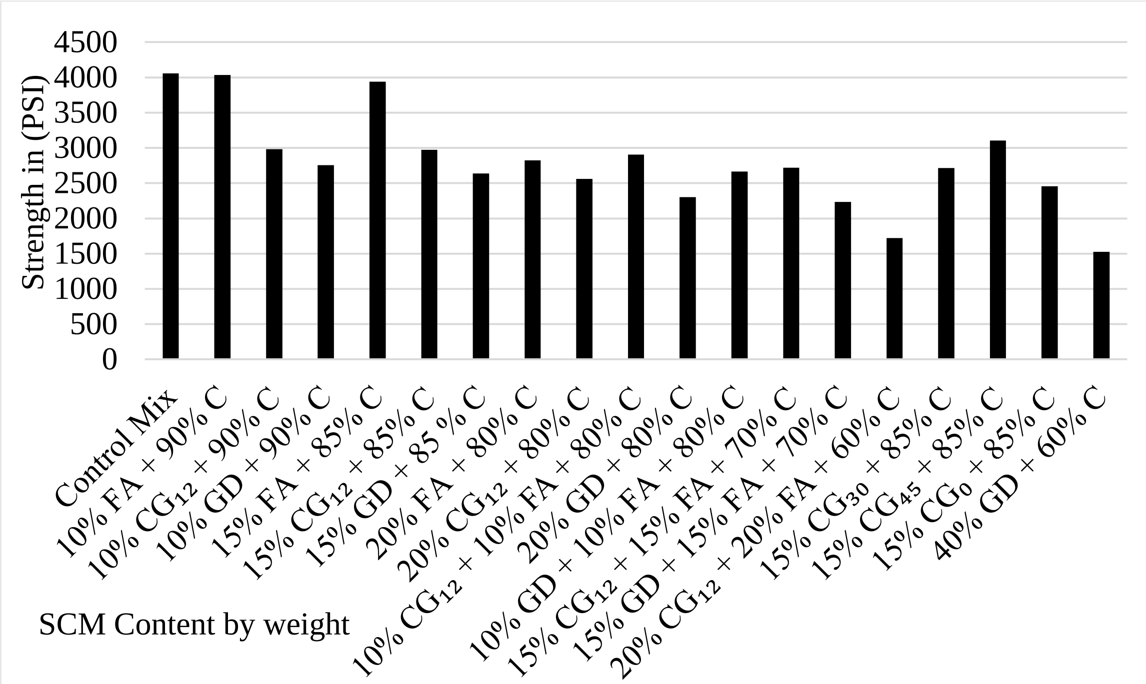

Figure A.6 Average 7-day mortar cube compressive strength of mix designs with different percent replacement of SCM; 3 replicates tested.

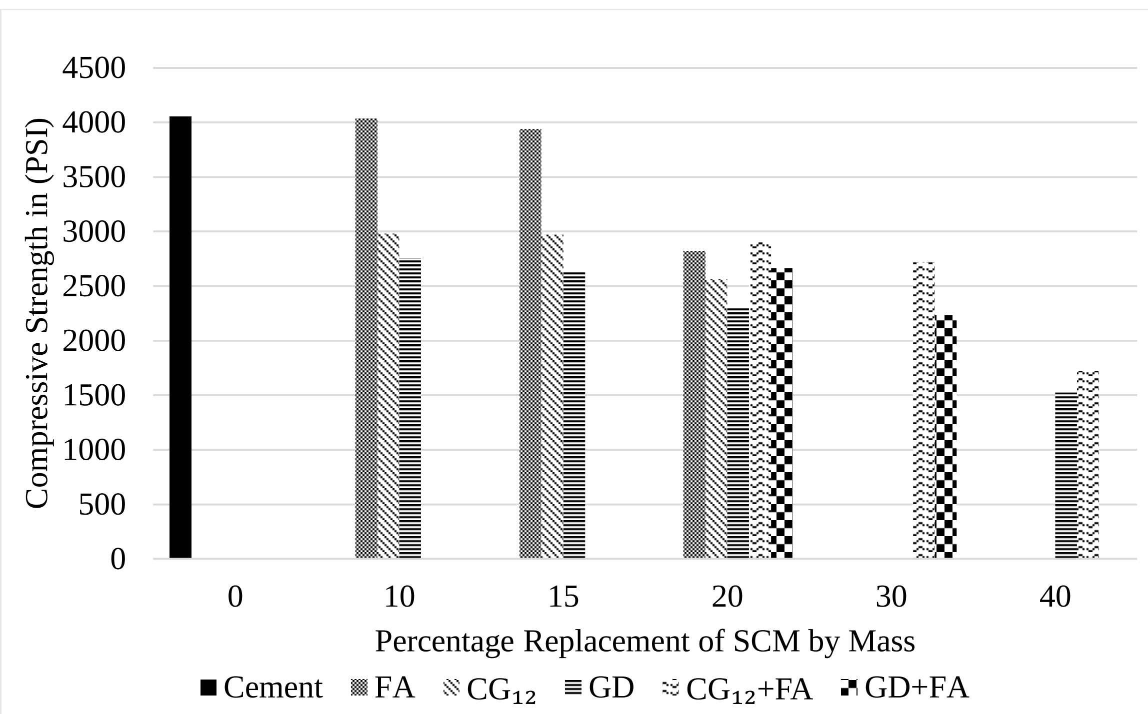

Figure A.7 Average 7-day strength comparison of mix designs with 10-40% replacement of cement by weight; 3 replicates tested.

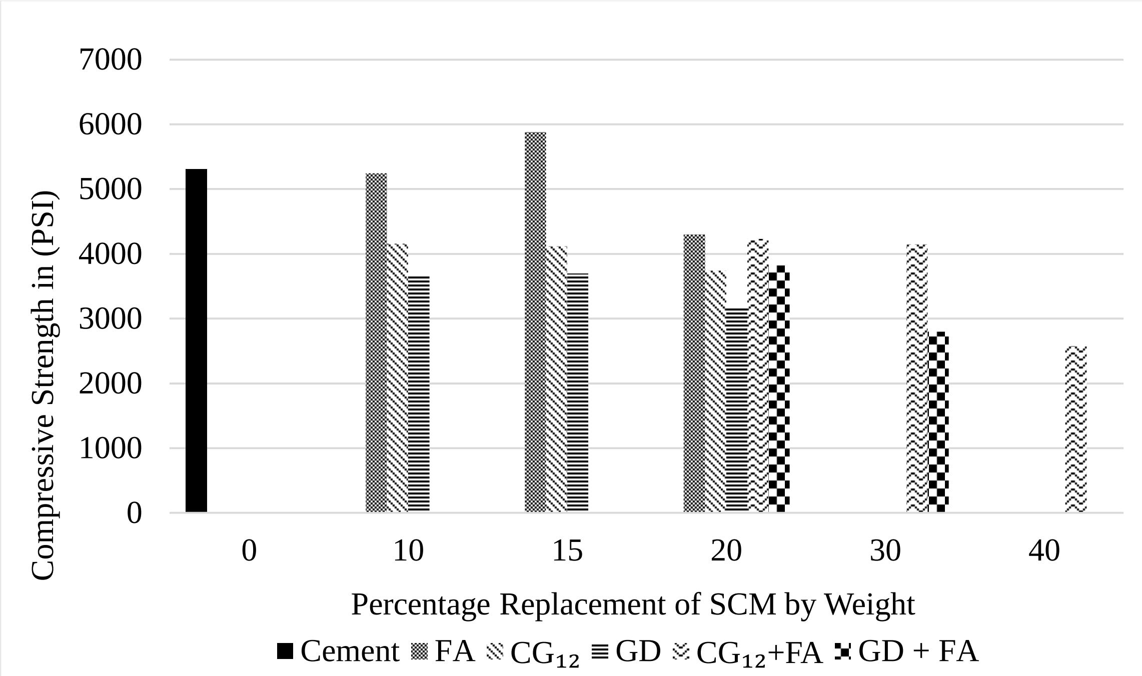

Figure A.8 Average 28-day strength comparison of mix designs with 10-40% replacement of cement by weight; 3 replicates tested.

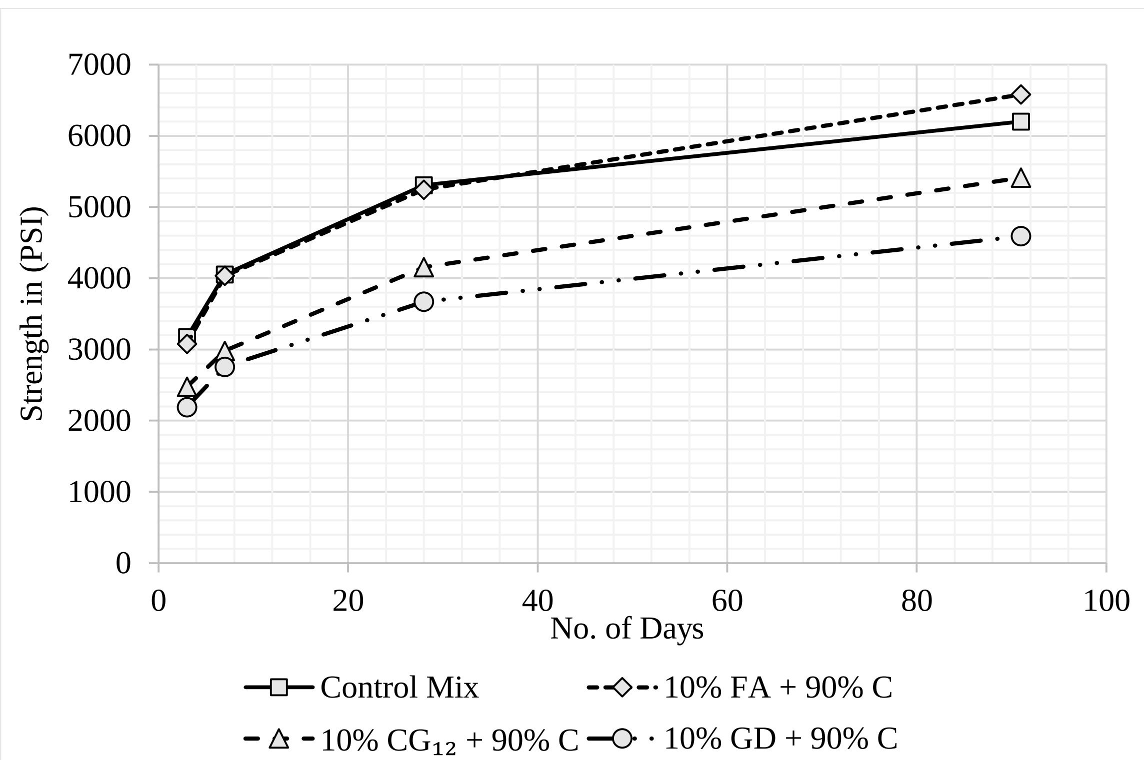

Figure A.9 Average strength comparison chart of 100% cement vs 10% cement replacement; 3 replicates tested.

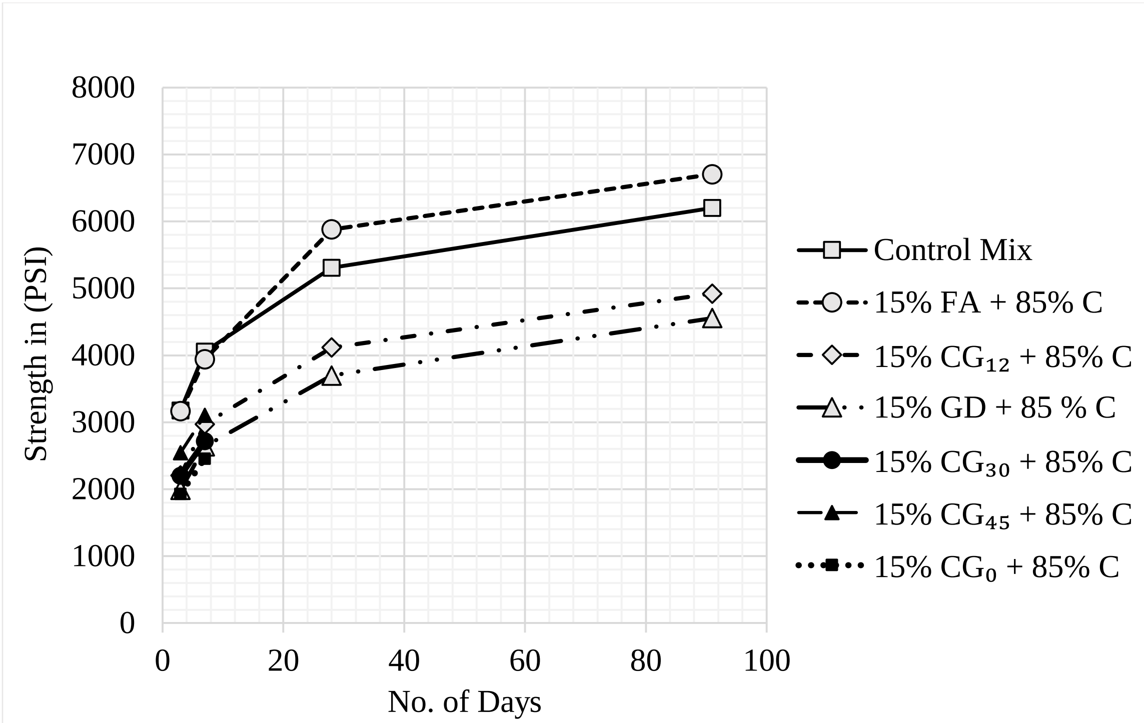

Figure A.10 Average strength comparison chart of 100% cement vs 15% cement replacement; 3 replicates tested.

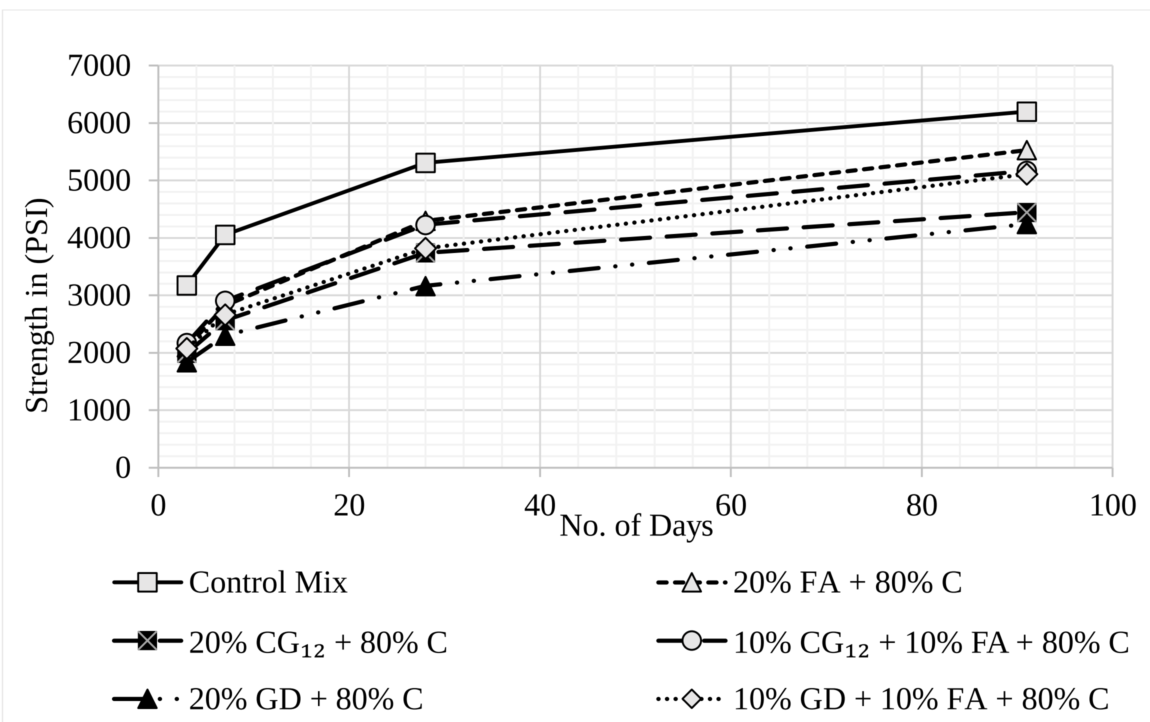

Figure A.11 Average strength comparison chart of 100% cement vs 20% cement replacement; 3 replicates tested.

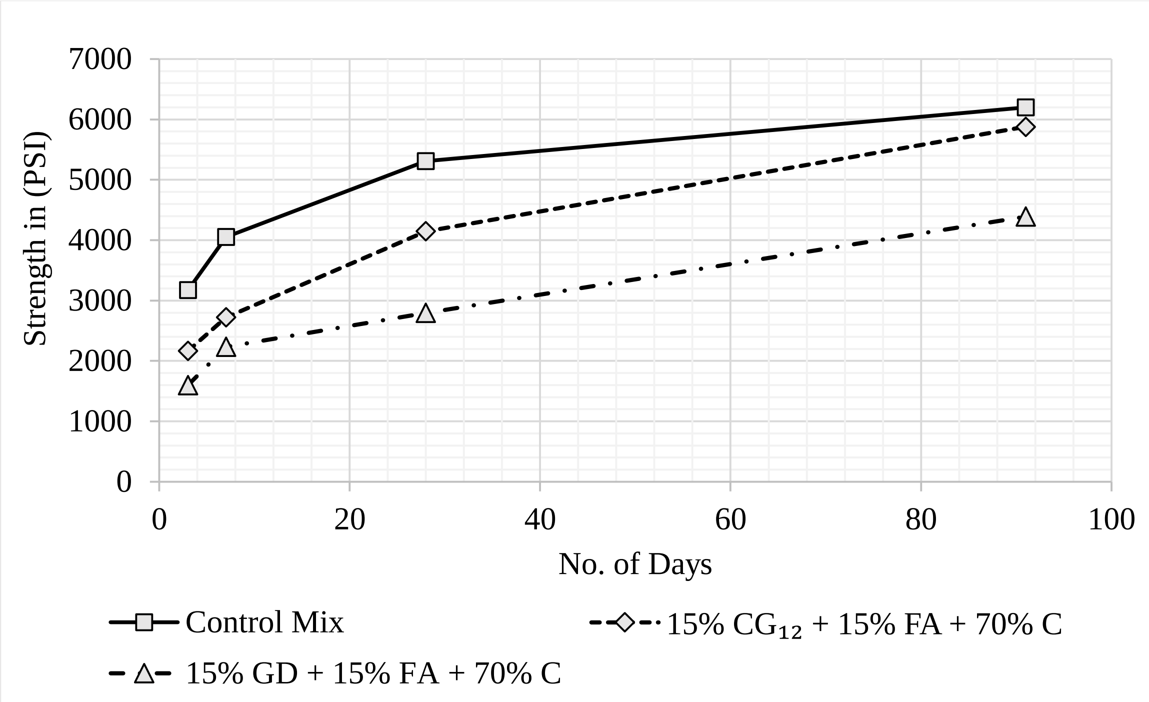

Figure A.12 Average strength comparison chart of 100% cement vs 30% cement replacement; 3 replicates tested.

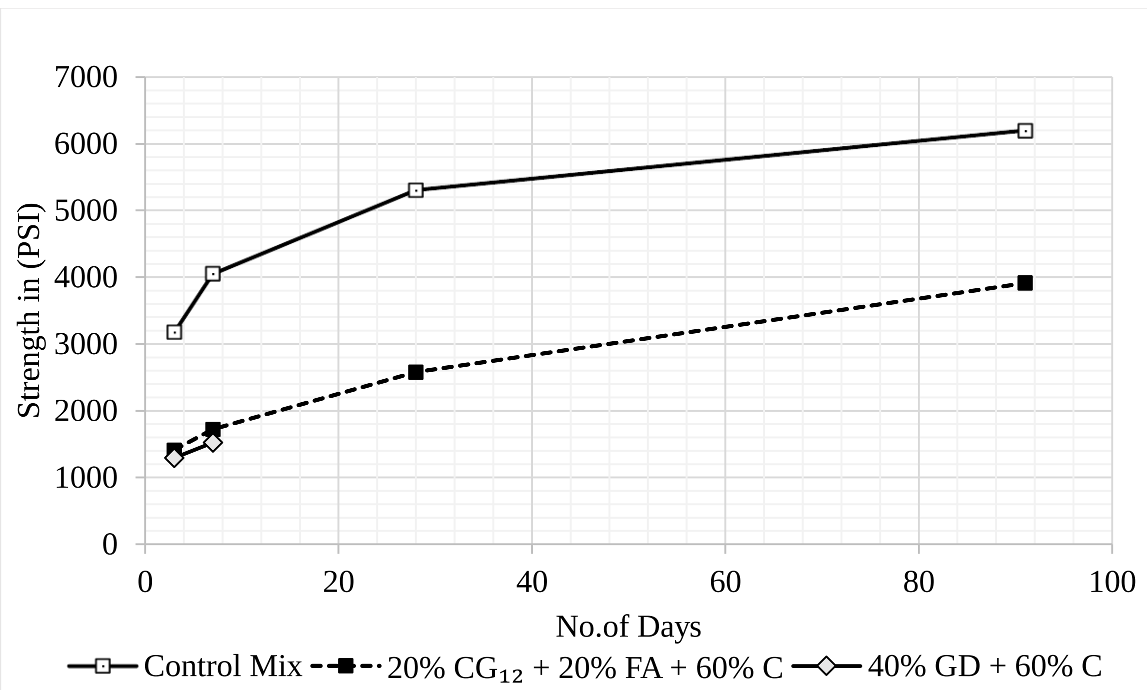

Figure A.13 Average strength comparison chart of 100% cement vs 40% cement replacement; 3 replicates tested.

REFERENCES

[1] U.S.A-EPA, 2010, "Municipal Solid Waste in the United States 2009 Facts and Figures," Office of Solid Waste (5306P), 1200 Pennsylvania Avenue, Washington DC, p.189, 2/25/2015, http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2009rpt.pdf.

[2] "Time it takes for garbage to decompose in the environment," U.S. National Park Service, Mote Marine Lab, Sarasota, FL, 2/25/2015.

[3] Shi, C., and Zheng, K., 2007, "A review on the use of waste glasses in the production of cement and concrete," Resources, Conservation, and Recycling, 52(2), pp. 234-247.

[4] Blue, J., 2013, "How Is Glass Recycled & Made Into New Products," SFGate, Demand Media 2/25/2015, http://homeguides.sfgate.com/glass-recycled-made-new-products-79174.html.

[5] U.S.A-EPA, 2011, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2010," U.S Environmental Protection Agency, Washington, DC, Office of Resource Conservation and Recovery, p. 58, 2/25/2015, http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

[6] U.S.A-EPA, 2009, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States," United States Environmental Protection Agency, Washington, DC, p. 11, 2/25/2015, http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2009-fs.pdf.

[7] U.S.A-EPA, 2014, "Wastes - Resources Conservation - Common Wastes & Materials," http://www.epa.gov/osw/conserve/materials/glass.htm.

[8] Online-Database, "Recycling Statistics - Glass Recycling Facts," Glass Packaging Institute, 1220 North Fillmore Street, Suite 400, Arlington, VA 22201, 2/25/2015, http://www.gpi.org/recycling/glass-recycling-facts.

[9] Jin, W., Meyer, C., and Baxter, S., 2000, ""Glascrete" - Concrete with glass aggregate," ACI Structural Journal, 97(2), pp. 208-213.

[10] Ahmad, S., and Aimin, X., 2004, "Value-added utilisation of waste glass in concrete," Cement and Concrete Research, 34(1), pp. 81-89.

[11] Topçu, İ. B., Boğa, A. R., and Bilir, T., 2008, "Alkali–silica reactions of mortars produced by using waste glass as fine aggregate and admixtures such as fly ash and Li_2CO3," Waste Management, 28(5), pp. 878-884.

[12] Du, H., and Tan, K. H., 2013, "Use of waste glass as sand in mortar: Part II – Alkali–silica reaction and mitigation methods," Cement and Concrete Composites, 35(1), pp. 118-126.

[13] Shi, C., 2009, "Corrosion of glasses and expansion mechanism of concrete containing waste glasses as aggregates," Journal of Materials in Civil Engineering, 21(10), pp. 529-534.

[14] Degirmenci, N., Yilmaz, A., and Cakir, O. A., 2011, "Utilization of waste glass as sand replacement in cement mortar," Indian Journal of Engineering and Materials Sciences, 18(4), pp. 303-308.

[15] Lee, G., Ling, T.-C., Wong, Y.-L., and Poon, C.-S., 2011, "Effects of crushed glass cullet sizes, casting methods and pozzolanic materials on ASR of concrete blocks," Construction and Building Materials, 25(5), pp. 2611-2618.

[16] Shi, C., Wu, Y., Riefler, C., and Wang, H., 2005, "Characteristics and pozzolanic reactivity of glass powders," Cement and Concrete Research, 35(5), pp. 987-993.

[17] Shao, Y., Lefort, T., Moras, S., and Rodriguez, D., 2000, "Studies on concrete containing ground waste glass," Cement and Concrete Research, 30(1), pp. 91-100.

[18] ASTM, 2012, "C150/C150M-12 Standard Specification for Portland Cement," ASTM International, West Conshohocken, PA, 2012, www.astm.org.

[19] ASTM, 2012, "C618-12a Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," ASTM International, West Conshohocken, PA, 2012, www.astm.org.

[20] Grace, W. R., 2009, "Force 10,000 D-Material Safety Data Sheet, D-06564, 10/30/2009, 62 Whittemore Avenue Cambridge, MA 02140 http://resapol.com/wp-content/uploads/2014/12/Grace_Force_10000_D_2009.msds_.pdf."

[21] ASTM, 2007, "C1260-07 Standard Test Method for Potential Alkali Re-activity of Aggregates Mortar-Bar Method," ASTM International, West Conshohocken, PA, 2007, www.astm.org.

[22] Ramasamy, U., 2014, "Alkali-Silica Reaction Resistant Concrete Using Pumice Blended Cement," Doctor of Philosophy, University of Utah, Salt Lake City, UT.

[23] Bergman, B., 9/15/2012, "Personal communication," Bobby Bergman, Materials Testing and Research Facility Manager at Headwaters Resources, ASTM C618/AASHTO

M295 Testing of Navajo Generating Station Fly Ash, 2650 Old State Highway 113, Taylorsville, GA 30178.

[24] ASTM, 2008, "C1567-08 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Material and Aggregate (Accelerated Mortar-Bar Method)," ASTM International, West Conshohocken, PA, 2008, www.astm.org.

[25] ASTM, 2006, "C778-06 Standard Specification for Standard Sand," ASTM International, West Conshohocken, PA, 2006, www.astm.org.

[26] BASF, "MasterGlenium 7710 data sheet," Master Builders Solutions, Ohio 44122-5544, USA, 2/25/2015.

[27] ASTM, 2013, "C494/C494M-13 Standard Specification for Chemical Admixtures for Concrete," ASTM International, West Conshohocken, PA, 2013, www.astm.org.

[28] ASTM, 2014, "C305-14 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency," ASTM International, West Conshohocken, PA, 2014, www.astm.org.

[29] ASTM, 2007, "C1437-07 Standard Test Method for Flow of Hydraulic Cement Mortar," ASTM International, West Conshohocken, PA, 2007, www.astm.org.

[30] ASTM, 2014, "C230/C230M-14 Standard Specification for Flow Table for Use in Tests of Hydraulic," ASTM International, West Conshohocken, PA, 2014, www.astm.org.

[31] ASTM, 2012, "C109/C109M-12 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens," www.astm.org.

[32] Lair, J., 9/20/2013, "Personal communication," John Lair, President and CEO at Momentum Recycling, Salt Lake City, UT.

[33] Bedford, C., 11/26/2014, "Personal communication," Christopher Bedford, Technical Service Representative at Headwaters Resources, Salt Lake City, UT 84171.

[34] Hanle, L. J., "CO2 Emissions Profile of the U.S. Cement Industry," U.S. Environmental Protection Agency 1200 Pennsylvania Ave, NW, Washington DC 20460, p. 14.

[35] Laker, T., 11/25/2014, "Personal communication," Todd Laker, Senior Technical Service Engineer at Holcim, UT.

[36] U.S-DOT, 2015, "Cement and Concrete," Federal Highway Administration, 1200 New Jersey Avenue, SE, Washington, DC 20590, 2/27/2015, http://international.fhwa.dot.gov/pubs/pl07027/llcp_07_05.cfm.

[37] D. S. Lane, 1998, "Evaluation of Concrete Characteristics for Rigid Pavements," Virginia Department of Transportation and the University of Virginia, Charlottesville, VA, 2/27/2015, http://www.virginiadot.org/vtrc/main/online_reports/pdf/98-r24.pdf.

[38] NRMCR, 2013, "Concrete price considerations-Cost of Concrete 2/25/2015," Ready Mixed Concrete Industry http://www.concretenetwork.com/concrete-prices.html.

[39] Bordelon, A. C., 2007, "Fracture behavior of concrete materials for rigid pavement systems," Master of Science, University of Illinois at Urbana-Champaign, Urbana, IL.

[40] Jeppsen, B. K., 11/26/2014, "Personal communication," Brian K. Jeppsen, Vice President at Hess Pumice, Malad City, ID 83252.