FLEXURAL LOAD CAPACITY OF HEAT-TREATED CONCRETE MIXED WITH RECYCLED GLASS AGGREGATE AND GLASS POZZOLAN

By

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Abstract

FLEXURAL STRENGTH OF HEAT-TREATED CONCRETE MIXED WITH RECYCLED GLASS AGGREGATE AND GLASS POZZOLAN

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This research focuses on determining the effects of adding glass aggregate and glass pozzolan to concrete that has been exposed to high temperatures. Previous work, based on finding the recommended proportions of recycled components for optimum results, was done to analyze the effects of adding recycled glass components to concrete. Based on those studies, a replacement ratio of 30% glass aggregates and 20% glass pozzolan was used in this project. The compressive strength of concrete has been extensively studied and has been shown to increase in strength when glass components are used in their correct proportions. Less research has been done on the flexural strength, and no previous research has been done on the flexural strength of glass concrete, which is the focus of this project. The hypothesis of this research is that concrete gains flexural strength with the addition of glass, after being exposed to high temperatures. To prove the hypothesis, six beams were made with regular concrete, six beams were made with 20% glass pozzolan as cement replacement, and six beams were made with 20% glass pozzolan as cement replacement and 30% glass aggregate as coarse aggregate replacement. After heat treating the beams and performing a 3-point flexural test, it was found that the samples containing 20% glass pozzolan as cement replacement had the highest load capacity, better heat resistance, and overall strong mechanical behavior, before and after heat treatment. The beams with glass pozzolan and glass aggregate showed less flexural strength than those of regular concrete before heat treatment; however, after being exposed to heat for one hour, their flexural strength was higher to that of regular concrete. The glass concrete also demonstrated an insulating effect, as its internal temperature was the lowest recorded during the heat treatment.

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Chapter 1

Introduction

1.1 Background

The construction industry continually evolves by developing new technology, methods, and materials. In an advanced world, where the population is increasing and the demand for improved infrastructure is a constant concern, the need for better and more sustainable materials grows as well. The need for sustainable construction materials has inspired researchers to find ways to recycle and reuse various products. Concrete is widely used in construction for many different purposes and in almost all infrastructures, such as road, bridges, and buildings. It can be molded to almost any shape, and provides a high structural capacity; however, its production is a major source of pollution in the environment that accounts for 5-10% of the CO_2 production worldwide (Tamanna, 2013). Fortunately, several materials, such as fly ash and silica fume, byproducts that are recycled from other production processes, can be added to the concrete mixture to reduce the amount of pollution created by its production and increase its structural capacity.

Recently, research has been done on the effects of adding glass to concrete mixtures. Glass is a material commonly found in containers, windows, automobile parts, etc., but after its useful life has ended, most of it ends up in the landfills. In the United States, about 9.4 million tons of glass are generated annually, with about two-thirds of it ending up in landfills and only one-third being recycled (Peyvandi, et al. 2013). Glass can be recycled and reused by collecting it from landfills or recollection centers, sending it to processing plants where it is crushed into smaller pieces, and then to factories where the glass culets are melted, and new products are made. Glass can be also used in concrete mixtures, either as cement replacement or as aggregate replacement. The main problem with using it is a chemical reaction, called an alkali-silica reaction, that forms a gel that can create voids inside the concrete, but this can be mitigated by using admixtures. The use of glass benefits the environment by reducing the volume of landfills and improves the structural properties of concrete by increasing its compressive strength (Adaway, et al. 2015). Also, since the unit weight of glass is less to that of concrete, the weight of the members can be reduced, thus reducing the amount of dead weight of a structure.

To better understand whether glass concrete is safe for structural use, its resistance to fire needs to be assessed. Glass becomes liquid under high temperatures, so it was reasonable to wonder whether its use in concrete might affect the structural capacity of the members. Although glass melts at high temperatures, this research showed that beams containing glass that are exposed to high temperatures gain flexural strength and become more ductile. This research can help clear the path to accepting the use of glass in concrete construction. This "green" concrete would benefit the environment by removing products from landfills and reducing CO_2 emissions caused by cement production, and the construction industry would benefit from using an abundant material that can enhance the material properties of concrete.

1.2 Problem Statement

Recycled glass has been added to concrete as an aggregate or cement replacement in an effort to make the concrete sustainable. The effects of fire exposure must be studied, however, in order to ensure the safety of buildings in which concrete and glass components are combined. Glass is a material that can be melted, thus the structural integrity of concrete with glass can be affected by exposure to high temperatures. Research has been conducted on the effects of fire on the compressive strength of concrete with glass components; however, the flexural strength has not been studied yet and is an important topic if this material is to be used in members such as beams or girders.

1.3 Objectives

The following objectives served as a guideline for the completion of this project:

- Perform a literature review to investigate optimum replacement rates,
- Design three concrete mixtures based on different parameters,
- Prepare and cast samples made with glass concrete,
- Expose the specimens to fire and perform flexural testing,
- Evaluate the results and compare them with the results of the conventional concrete samples,
- Perform numerical analysis to compare results, using Excel software, and
- Draw conclusions and make recommendations for future research needs.

Chapter 2

Literature Review

2.1 The Use of Glass in Concrete.

Concrete is used for construction worldwide because of its versatility. It is in high demand, and a variety of materials are needed to fulfill the construction industry's many uses for the product. Cement, coarse aggregate and fine aggregates are all used in concrete production, and producing these materials creates environmental pollution and degradation by generating CO_2 emissions. Cement production accounts for 5-10% of the overall CO_2 production in the world (Tamanna, 2013). In addition to the basic ingredients, various materials that are byproducts of industrial processes, such as fly ash and silica fume, can be added to concrete to improve its mechanical performance and help reduce pollution by reducing waste and CO_2 emissions. New materials are constantly being tested to see if they can be used in concrete mixtures, and one of these materials is glass, which is very accessible. Glass can be added to concrete either as aggregate or as pozzolan, but it presents a major challenge, as the combination of concrete and glass causes an alkali-silica reaction (ASR). Efforts have been made to mitigate the effects of the ASR by adding admixtures to the concrete.

2.1.1 Effects of Glass as Aggregate Replacement on Compressive and Flexural Strength

When used as an aggregate, glass can serve as a replacement for both fine and coarse aggregates. Different replacement ratios have been used in an effort to find the optimum glass aggregate replacement ratio, and several studies have been performed to analyze the effects of the various replacement ratios on the compressive strength of concrete. Wang et al. (2015) performed research to investigate the effects of the compressive strength of concrete by using 10%, 20%, and 30% coarse glass aggregate as a replacement. Their results showed an overall reduction of compressive strength of the concrete-glass mixtures compared to the control samples, and the reduction increased as the amount of glass in the mixture increased. Additionally, Fawaz et al. (2018) studied the effects of glass used as coarse aggregates in concrete, and their research showed that the optimum replacement ratio is attained by using coarse glass aggregates to replace one-third of the natural coarse aggregate, Similarly, Adaway et al. (2015) recommends using 30% of fine glass aggregate for optimum compressive strength results, as proportions exceeding 30% negatively affect the performance of concrete. Overall, the literature seems to suggest that the aggregate replacement should be around 30%.

Recycled glass can come from many different sources, such as glass bottles, windshields, etc. that often end up in the landfill. This source of glass can help reduce the volume of landfills. Ganiron Jr. (2013) studied the compressive strength of concrete, using glass from recycled bottles, and the concrete samples containing glass as aggregate replacement were found to have lower compressive strength and lower modulus of elasticity compared to the control sample. Table 2.1 summarizes the results of this study.

Table 2.1 Effects of Glass Replacement on Concrete Properties (Ganiron Jr. 2013).

Sample	Compressive strength, ksi (MPa)	Modulus of Elasticity, ksi (MPa)
Control	3.70 (25.54)	4098.96 (28261.35)
25% glass replacement	1.59 (10.96)	2669.82 (18407.76)
50% glass replacement	1.68 (11.60)	2870.66 (19792.52)
75% glass replacement	1.75 (12.08)	2862.07 (19733.29)
100% glass replacement	1.47 (10.12)	2473.55 (17054.57)

Research has also been conducted to a more limited degree on how using glass aggregates affects the flexural strength of concrete. The literature shows that the use of recycled glass aggregates in concrete generally reduces its flexural strength. According to a study of the mechanical performance of concrete made with glass aggregate, the flexural strength goes down as the ratio of glass increases (Serpa et al., 2015); however, it showed that coarse aggregate was more beneficial than fine aggregate. The same decrease in strength can be seen in a similar research done by Canbaz et al. (2004), which showed a decrease in flexural strength with an increase in the glass replacement ratio. As the literature suggests, a decrease in flexural strength is expected glass aggregates are used in concrete mixtures.

2.1.2 Effects of Glass as Cement Replacement on Compressive and Flexural Strength

When glass is ground to a particle size below 300 µm, it obtains its pozzolanic properties and is a promising replacement for cement. The reaction occurs when the glass particles encounter the lime and the water found in concrete mixtures. Below a particle size of 100 µm, glass can have a pozzolanic reactivity greater than fly ash (Tamanna et al., 2013). Because of this property, glass powder has been used as pozzolan in previous research.

The effects of the glass pozzolan on the compressive strength of concrete have been studied by other researchers, and the 28-day compressive strength has been compared with the strength of regular concrete. At 28 days, the compressive strength is more reduced in samples with a 10%, 20% and 30% glass powder replacement than in regular concrete (Wang et al., 2015). However, the glass pozzolan helps the concrete develop more strength as it ages, and eventually, the strength of concrete with glass pozzolan is higher than that of regular concrete. Peyvandi et al. (2013) showed that concrete mixtures with glass as cement replacement gained strength over time. Although, at 28 days the compressive strength of regular concrete was still higher, the compressive strength of concrete with a 20% glass powder replacement was higher after 56 days. Figure 2.1 shows the results from this research.

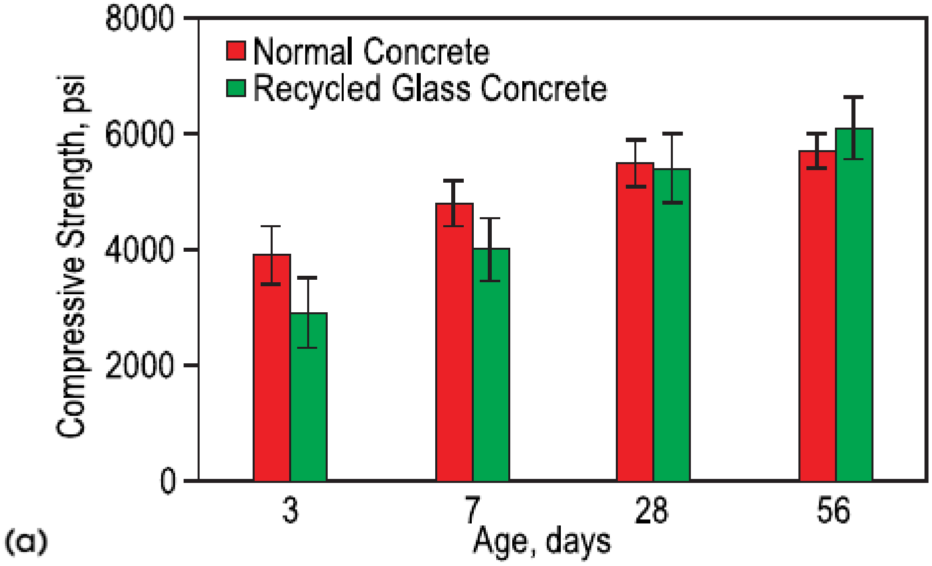


Figure 2.1 Effects of Glass Powder Replacement on Compressive Strength (Peyvandi et al. 2013)

The optimum replacement ratio recommended by literature is approximately 20% which, as previously seen, helps increase concrete's strength after 56 days (Peyvandi et al. 2013). In a similar research, Anwar (2016) concluded, based on his experimental results, that it is feasible to replace up to 20% of cement with glass powder.

Flexural strength is an important mechanical property; hence researchers have assessed the effects of glass pozzolan on the flexural performance of concrete. As with compressive strength, a slight reduction in strength is expected when glass powder is used, as evidenced by the study performed by Aseel AL-Zubaid et al. (2017), in which they researched the effects of different types of glass on the flexural strength of concrete when it was used as cement replacement. Three kinds of glass were used as replacement: brown glass, green glass, and neon glass, and the research showed that all of the types of glass caused a decrease in flexural strength when compared to the control sample; the neon glass performed 13% better than the other two types of glass.

Similar studies showed the same trend of a decrease in flexural strength. The research performed by Peivandi, et al. (2013) showed a decrease in flexural strength in samples at 28 days after casting; however, the flexural strength of the concrete with 20% glass powder increased more at 56 days than the regular concrete. Overall, the flexural strength increased as the concrete aged. Figure 2.2 shows this trend.

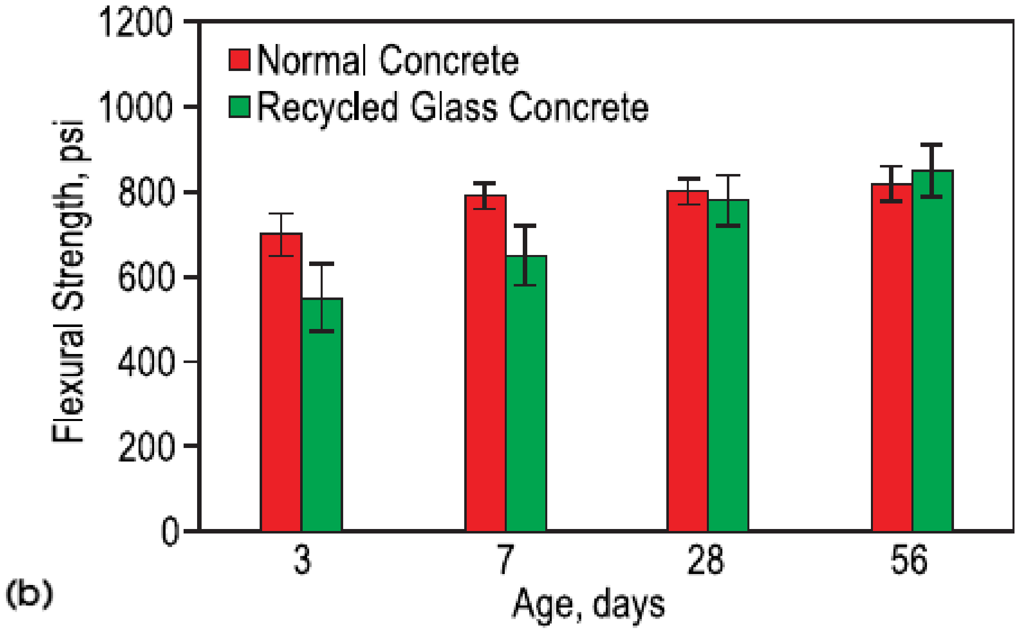


Figure 2.2 Effects of Glass Powder Replacement on Flexural Strength (Peyvandi et al. 2013)

Glass pozzolan can be mixed with other materials as well, with no negative impacts on the mechanical performance of the concrete. As an alternative to silica fume, a mixture of glass powder with fly ash was shown to increase the flexural strength of concrete (Belachew et al., 2018). When the silica fume replacement was substituted using 50% fly ash and 50% glass powder, the flexural strength of samples increased up to 30.58%. This shows that using both fly ash and glass powder is more beneficial than just using the traditional silica fume.

As can be seen, the research reflects a varied range of results, with some studies showing that glass can benefit the mechanical performance, and others saying that glass slightly decreases the strength of concrete. This conflict suggests that more research is needed on this topic.

2.2 Previous Research with Fire Exposure.

The effects of elevated temperature on concrete that contains recycled glass has been previously studied, and the literature shows how it affects the mechanical properties such as compressive strength and split tensile strength. A wide range of parameters were used, including different proportions of glass in the mixture, the type of recycled glass used, and the temperature ranges. No previous research has been done on flexural strength after heat exposure.

Research was conducted on the effects of elevated temperature on the compressive strength of concrete containing glass powder as cement replacement (Olofinnade et al. 2017). The cement that was used was partially replaced by 0, 15, 18, 21, 24, 27 and 30 percent of glass powder and a constant water cement ratio of 0.5, The samples were heat treated and tested at four temperatures: 60, 150, 300 and 500 degrees Celsius. The results showed a decrease in compressive strength as the temperature increased, and found that the concrete containing 21% of glass powder replacement had higher residual compressive strength than that of the control mix for temperatures up to 500 degrees Celsius. The control sample possessed a higher compressive strength compared to the other mixes at room temperature. The samples with cement replacement of 24-30% showed a significant loss of strength compared to the control sample.

The effects of elevated temperatures on the compressive strength and split tensile strength of concrete containing recycled glass powder were studied by Shivaprasa et al. (2016). The samples were casted as cubes and cylinders, with cement replacements of 0, 5, 15, and 20% of glass powder. The samples were heat treated to four temperatures: 100, 200, 300 and 400 degrees Celsius, then the compressive strength and split tensile strength tests were performed. The study showed that the mixes containing glass powder up to 20% have higher compressive strength at elevated temperatures; the maximum compressive strength was attained when 10% glass powder replacement was used. The split tensile strength of concrete also increased for the samples containing glass powder. Figures 2.3 and 2.4 show the results from this study.

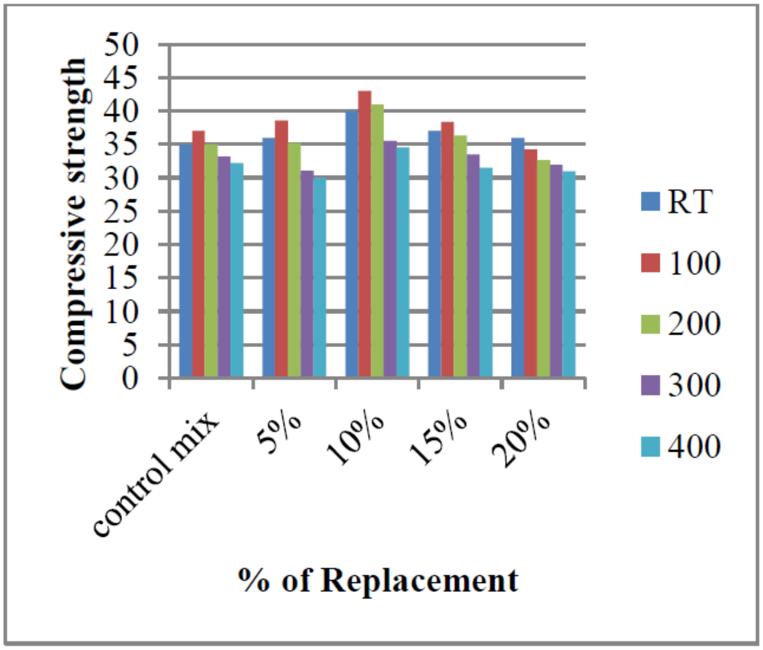


Figure 2.3 Compressive Strength of Concrete Containing Glass Powder (Shivaprasa et al. 2016)

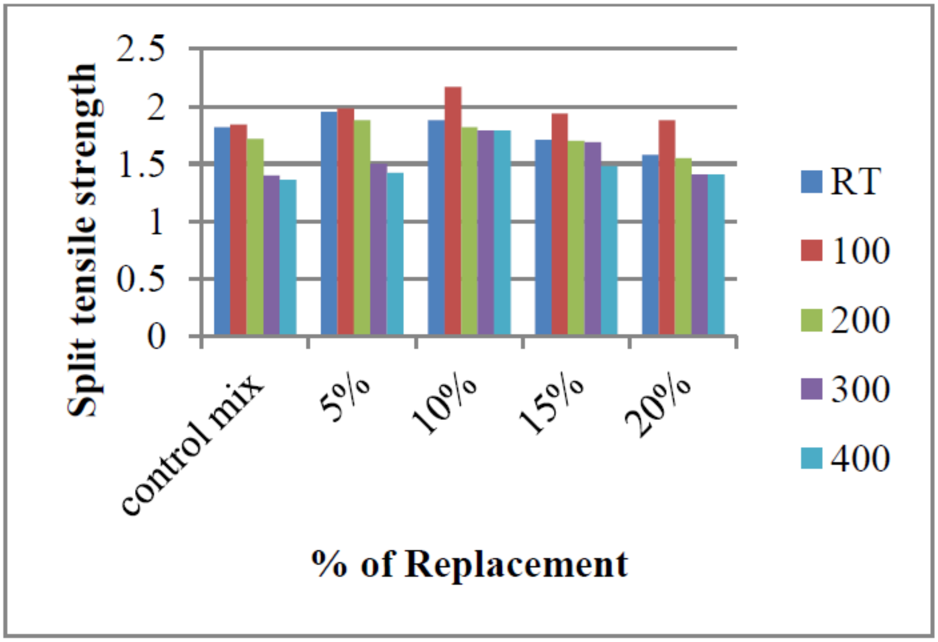


Figure 2.4 Split Tensile Strength of Concrete Containing Glass Powder (Shivaprasa et al. 2016)

Research has also been performed on samples with glass used as glass aggregate replacement after heat exposure. Mohamad J. Terro (2006) studied the effects of elevated temperature of concrete made with recycled glass aggregate by using mixes containing fine glass aggregate, coarse glass aggregate, and a mixture of both. Cubes were casted and heat treated to six temperatures: 20, 60, 150, 300, 500 and 700 degrees Celsius. The compressive strength test was performed after heat treatment. The experiment showed that the compressive strength of all the mixes decreased as the temperature increased. The control samples had a higher compressive strength at room temperature. The samples containing 10% fine glass aggregates, coarse glass aggregates, and a combination of both showed a higher compressive strength compared to the control samples up to 700 degrees Celsius. It was noted that when the temperature surpassed 700 degrees, all of the samples containing recycled glass had similar compressive strength, regardless of the replacement percentage and aggregate size. According to the author, this could be attributed to the approach of the glass to its melting threshold (700 – 800 degrees Celsius for soda-lime glass) since the high temperature softens the glass, eliminating the effect of the size of the glass aggregate on the compressive strength.

Previous research conducted on the compressive strength of samples with glass components after heat treatment showed that glass is beneficial to concrete that is exposed to fire. The glass seems to be effective at resisting high temperatures, which improves the performance of the entire mixture.

2.3 Alkali-Silica Reaction

Recycled glass has been used as a partial replacement for cement and aggregates but when it is used as aggregate replacement, the alkali-silica reaction (ASR) becomes a problem. This reaction is surface dependent; therefore, larger particles that present in fine and coarse aggregates can lead to the development of ASR (Tamanna et al., 2013). According to Wang et al. (2015), this is the reason why recycled coarse glass is not allowed in structural construction. However, this reaction is not developed exclusively by glass aggregates. In the article *Concrete with Waste Glass as Aggregate*, the author states that the problem of the alkali-silica reaction is not restricted to glass aggregate only; it also can occur in regular concrete if the aggregate contains “certain siliceous rocks and minerals, such as opaline chert, stained quartz and acidic volcanic glass,” as described by the definition of ACI Committee 116 (Meyer at al., 2001). Meyer explains that ASR is a long-term process and is difficult to predict in regular aggregates. On the other hand, whenever glass aggregate is used, the ASR is expected, and action can be taken to mitigate it.

The alkali-silica reaction process is explained in the book, *The Alkali-Silica Reaction in Concrete* (Swamy, 1992), as a process that is the result of the reaction between the alkali pore fluids in the concrete and siliceous components of the aggregate particles. This reaction creates an alkali-silica gel that is hydrophilic and increases in volume as it absorbs moisture, creating internal pressures that are large enough to damage the composition of the concrete.

The alkali-silica reaction can be described as a two-step process. First, an acid-based reaction creates a gel that is formed by the hydrolysis of the reactive silica by the hydroxide. Second, the gel absorbs water, leading to increase in its volume. As Swamy explains it, the pressure produced by the expanding gel induces the formation of microcracks close to the reaction sites. These microcracks propagate and coalesce to produce cracking within the fabric of the concrete, affecting the structural integrity of the element.

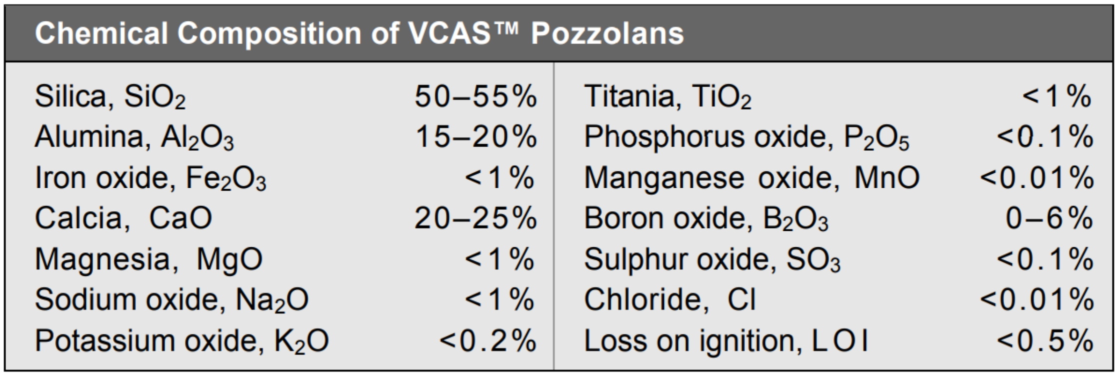
Efforts have been made to find way to reduce the effects of ASR in concrete mixtures. Literature shows that additives can be used to reduce the effects of the alkali-silica reaction on concrete with glass. The article by Wang et al. (2015) indicates that fly ash can reduce the possibility of ASR occurring. The use of fly ash as a way to reduce effects of the alkali silica reaction is further supported by As'ad Munawir (2017), who notes that when coarse or fine aggregates are used, fly ash must be added to mitigate the negative effects of ASR. Besides the use of additives, the type of glass used in concrete can be used to avoid the effects of the alkali-silica reaction. Using glass as pozzolan can prevent the occurrence of ASR. As noted by the research done by Tamanna et al. (2013) ASR is a surface-area-dependent phenomenon; therefore, the use of glass grounded to a particle size of 300 μm or smaller glass reduces the possibility of effects from a alkali-silica reaction.

2.4 VCAS Glass Pozzolan Properties

Vitreous calcium aluminosilicate (VCAS) is a pozzolan produced from recycled glass that is engineered and designed to be used in Portland cement, mortar and concrete products.

After the glass is properly sized and dried, it is finely ground and processed using high efficiency classifiers. The product is a fine bright white powder with a consistent, highly reactive chemical composition, which results in a quality pozzolan for concrete applications. Table 2.4.1 shows the chemical composition of the VCAS pozzolans as reported on the manufacturer's data sheet.

Table 2.2 Chemical Composition of VCAS Pozzolans (Vitrominerals 2017)



Chemical Composition of VCAS™ Pozzolans			
Silica, SiO_2	50–55%	Titania, TiO_2	<1%
Alumina, Al_2O_3	15–20%	Phosphorus oxide, P_2O_5	<0.1%
Iron oxide, Fe_2O_3	<1%	Manganese oxide, MnO	<0.01%
Calcia, CaO	20–25%	Boron oxide, B_2O_3	0–6%
Magnesia, MgO	<1%	Sulphur oxide, SO_3	<0.1%
Sodium oxide, Na_2O	<1%	Chloride, Cl	<0.01%
Potassium oxide, K_2O	<0.2%	Loss on ignition, LOI	<0.5%

VCAS pozzolans are composed largely of oxides of silicon, aluminum, and calcium with no deleterious impurities. The pozzolan reacts with calcium hydroxide produced during the Portland cement's hydration phase and forms additional cementitious compounds such as calcium silicate and alumino-silicate hydrates. As previously stated, an alkali-silica reaction is a major issue when recycled glass products are used in concrete production. When used as a cement replacement, VCAS is effective at controlling the expansion caused by the alkali-silica reaction (Vitrominerals, 2017).

The pozzolan comes in different grades like VCAS-8 VCAS-MicronHS, VCAS-140 and VCAS-160. For this project, VCAS-8 was used as a cement replacement. Table 2.4.2 summarizes the physical properties of this pozzolan.

Table 2.3 Physical Properties of VCAS Glass Pozzolan (Vitrominerals 2017)

Physical Properties of VCAS-8 Pozzolan	
Specific gravity	2.6
Bulk density (lb./ft^3)	50-55
Percent passing No. 325 mesh	95
Pozzolanic strength index (%)	106
Brightness (%)	87-90
Melting point (°C)	1200
Hardness (Mohs)	5.5

According to the manufacturer's information, VCAS pozzolan can be used to replace from 15% to 30% of Portland cement without negative consequences. VCAS pozzolans have a 17.5% lower specific gravity than Portland cement, which is an important consideration when replacing the cement. The specifications given by the manufacturer for mix designs are the following:

1- Replacing cement: For every pound of cement removed from the mix, add back 0.825 lbs. of VCAS to achieve equal volumes. All other ingredients stay the same (Vitrominerals, 2015).

2- Adding VCAS to existing mixes: Add 25 lbs. of VCAS for every 94 lb. bag of cement. This increases the volume of the cement paste by 32%. Increase the amount of sand by 30% and water/admixtures by 25% (Vitrominerals, 2015).

Chapter 3

Experimental Procedure

3.1 Introduction

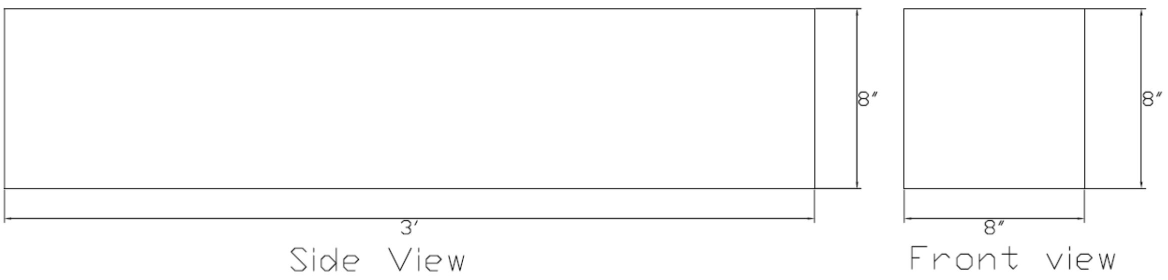
Samples were casted and tested to investigate the effects of glass in concrete mixes exposed to elevated temperatures. Two variables were considered in the experimental design: the concrete mix contents and the exposure to temperature. Three concrete mixes were designed to test the effects of concrete mixed with different kinds of recycled glass:

- Plain concrete (control),
- Concrete with 20% glass powder (VCAS) as cement replacement,
- Concrete with 20% glass powder (VCAS) as cement replacement and 30% glass aggregate as coarse aggregate replacement.

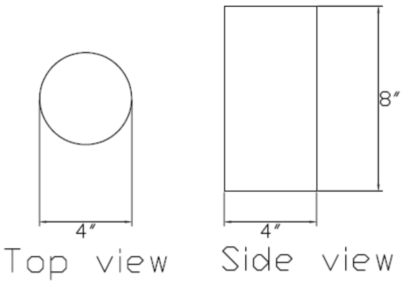
The variable for the temperature was the duration of the beam exposure to heat. The heat treatment was performed following the ASTM E119 standard for fire testing. Following this standard, two exposure times were determined:

- 30 minutes
- 1 hour

A total of 18 beams were prepared to perform the test, with six beams cast from each concrete mixture. Cylinders were cast as well to measure the compressive strength. The dimensions of the beams were 8” x 8” x 36”; the cylinders had a 4” diameter and were 8” long. The sample dimensions are shown on Figure 3.1



Beam Dimensions



Cylinder Dimensions

Figure 3.1 Sample Dimensions

Although concrete offers very little flexural resistance, no reinforcement was used in the beams, as the purpose of the experiment was to evaluate the effects of glass mixed with concrete on the flexural behavior of concrete. By not adding reinforcement, only the concrete's strength would be tested.

The testing schedule was designed using the "Factorial Design" method. In this research, the fractional factorial method, a statistical method that facilitates studying the effects of several parameters, while using a reduced number of samples, by grouping the parameters (NIST/SEMATECH handbook, 2012). This is a modification of the full factorial method, which significantly reduces the number of samples needed. For this experiment, two samples were designated for each variable. The total number of beams is 24 using the full factorial method.

However, based on the fractional factorial method and the fact that the plain concrete beams would have the same properties for several criteria, the total number of beams can be reduced to 18. Table 3.1 shows the experimental beam schedule for testing.

Table 3.1 Experimental Design.

No. of criteria	Glass powder replacement per cement volume.	Coarse glass aggregate replacement per aggregate volume	Heat treatment	No. of beams	Remarks
1	20%	-	-	2	Control
2	0%	-	-	2	Control
3	20%	-	½ hr.	2	-
4	0%	-	½ hr.	2	-
5	20%	-	1 hr.	2	-
6	0%	-	1 hr.	2	-
7	20%	30%	-	2	Control
8	0%	0%	-	-	Control
9	20%	30%	½ hr.	2	-
10	0%	0%	½ hr.	-	-
11	20%	30%	1 hr.	2	-
12	0%	0%	1 hr.	-	-
			Total	18	

3.2 Concrete Mix Design

The concrete mix was designed using the ACI volumetric method (1985). The target strength for the concrete design was 3500 psi. The mixing proportions were calculated based on this initial determination, and the calculations were performed for one cubic yard of concrete. First, the water-to-cement ratio was set as 0.51 for all of the mixes to assess the effect of adding glass on the concrete’s workability. Once the water-cement ratio was defined, the amount of cement required for each mix was calculated. Using this calculated value, the amount of VCAS required for the mixes using glass powder as replacement for cement was calculated. Since the volumetric method was used, the cement replaced was calculated by volume instead of by weight. The replacement ratio, 20% of Portland cement, was based on the literature review and the glass pozzolan manufacturer's recommendations. Since glass has a lower unit weight than concrete, the weight of the volume of glass needed to replace the same volume of cement was slightly lower. The specific gravity of the VCAS pozzolan is 2.6, while the specific gravity of the regular Portland cement is 3.15. According to the manufacturer specifications, for every pound of cement removed from the mix, 0.825 lbs. of VCAS must be added to achieve equal volumes.

The aggregate proportions were calculated similarly, using the ACI volumetric method (1985). The maximum coarse aggregate size for the mix was set at 1 inch. A coarse aggregate replacement of 30% was determined based on the literature review findings. The glass was donated by the company "Strategic Materials," and the glass aggregate was grounded and sieved to a maximum size of 5/8". This is the standard glass cullet size used in the manufacture of recycled glass products and is below the 1" maximum aggregate size determined for the natural coarse aggregate.

Figures 3.2, 3.3, 3.4 and 3.5 show the glass aggregate, VCAS glass pozzolan, natural coarse aggregate and sand used in the concrete mixtures, respectively. The mix design calculations are given in Appendix A.

Figure 3.2 Glass Aggregate Used as Coarse Aggregate Replacement

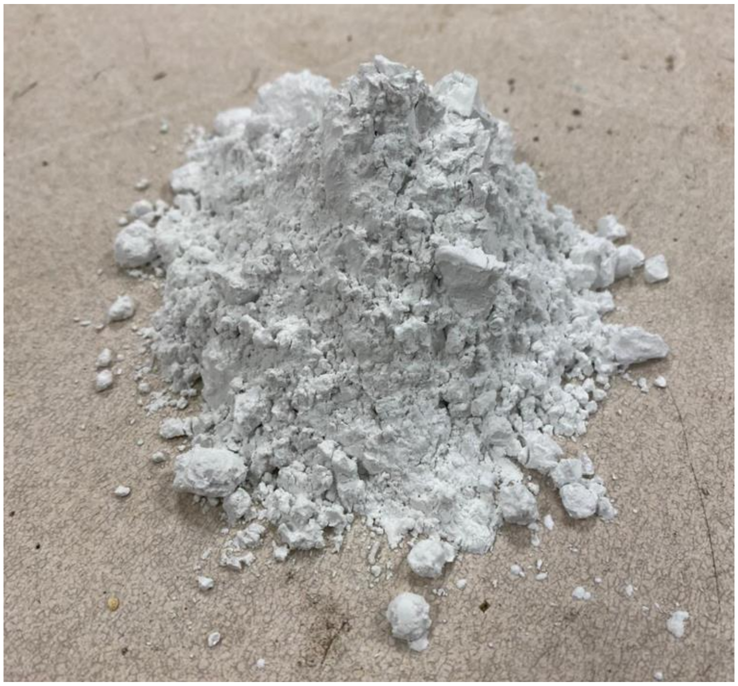


Figure 3.3 VCAS Glass Pozzolan Used as Cement Replacement

Figure 3.4 Natural Coarse Aggregate Used

Figure 3.5 Fine Aggregate Used (Sand)

The concrete was mixed and casted in the laboratory. The volumes of material calculated by the ACI volumetric design were converted to weight since adding the materials to the mixer based on their weight would render the mixing process more accurate and convenient. The materials needed for the project are presented in tables 3.2, 3.3, 3.4 and 3.5.

Table 3.2 Total Material Proportions Needed for the Project (per cu.yard)

Material	Weight required (lb)
Water	300
Cement	590
Coarse aggregate	1744
Fine aggregate	1430
VCAS	98
Coarse glass	312

Table 3.3 Material Proportions Required for One Beam of Plain Concrete

Material	Weight required (lb)
Water	14.7
Cement	28.91
Coarse aggregate	85.45
Fine aggregate	70

Table 3.4 Material Proportions Required for One Beam with 20% VCAS as Cement Replacement

Material	Weight required (lbs.)
Water	14.7
Cement	23.13
Coarse aggregate	85.45
Fine aggregate	70
VCAS	4.76

Table 3.5 Material Proportions Required for One Beam with 20% VCAS as Cement Replacement and 30% Glass Aggregate as Coarse Aggregate Replacement

Material	Weight Required (lbs.)
Water	14.7
Cement	23.13
Coarse aggregate	59.81
Fine aggregate	70
VCAS	4.76
Glass Aggregate	24.10

3.3 Sample Casting and Curing

For this experiment, 18 beams were proposed for testing. The formwork was built with reusable wooden forms that had been cleaned to remove the concrete from a previous cast. Once all of the wood was cleaned, the boxes were assembled. Figure 3.6 shows the typical formwork for a beam.

Figure 3.6 Beam Formwork Assembly

Casting was done at the University of Texas at Arlington Civil Engineering Laboratory Building (CELB). A concrete mixer with a capacity of 9 cubic feet was used to mix the concrete; however, operating the mixer at full capacity would not yield a good mixture, so it was done in 6 batches. Each batch was enough to cast about 2 beams at a time. The materials (cement, gravel, sand, glass aggregate, VCAS pozzolan and water) were weighted in the corresponding proportions and added to the mixer. The mixer was powered on while the materials were being added. Once all of the materials were inside the drum, a mixing time of two minutes was allowed to achieve a uniform mixture. Once the mixing was completed, the concrete was placed on the wooden formwork and was vibrated with a vibrator. It was hand finished for a uniform and smooth surface. Figures 3.7, 3.8, 3.9, 3.10 and 3.11 show pictures of the casting.

Figure 3.7 Concrete Mixer

Figure 3.8 Materials Being Added to the Mixer

Figure 3.9 Concrete After Mixing

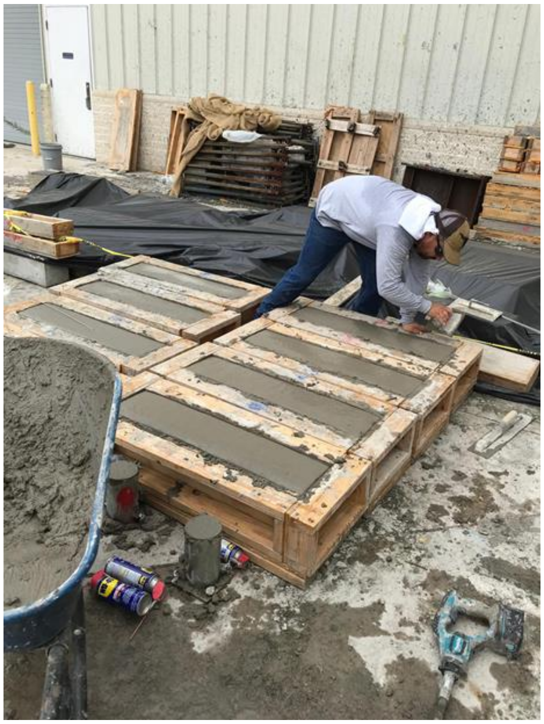


Figure 3.10 Finish of Concrete Beams

Figure 3.11 Cast Beams and Cylinders

To better understand the temperature distribution on the beams, a thermocouple was placed in the middle of 12 beams while they were being casted, and they were embedded 4 inches into the concrete. Special care was taken to prevent damage to the thermocouple sensors and to make sure that they were placed correctly. Figures 3.12 and 3.13 show diagrams of the placement of the thermocouple.

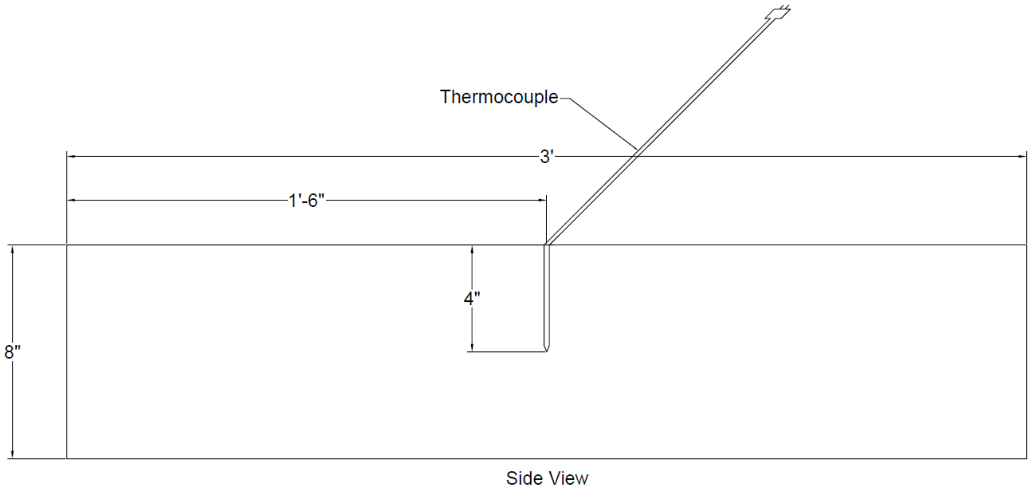


Figure 3.12 Beam with Thermocouple – Side View

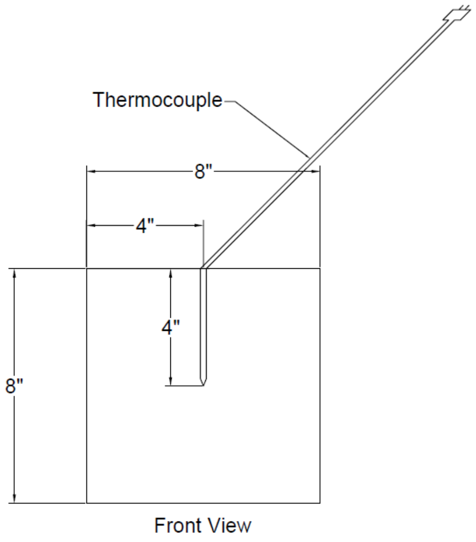


Figure 3.13 Beam with Thermocouple- Front View

Three cylinders were cast for each concrete mixture, in three layers, with each layer being tamped with a rod 25 times to achieve a uniform concrete distribution on the sample. The slump test, air content test, and temperature were recorded following ASTM C143 (2015), ASTM C231 (2017) and ASTM C1064 (2017), respectively. Figures 3.14 and 3.15 show the equipment that was used for the fresh concrete tests and pictures taken during casting.

Figure 3.14 Slump Test.

Figure 3.15 Air Content Apparatus

After casting, a curing compound was applied to the surface of the concrete. This method was used as an alternative to curing the samples with water to maintain the humidity. All of the samples were covered after the compound was applied to avoid direct contact with the sun.

3.4 Heat Treatment

When a fire occurs inside a structure, the fire department's response time depends on several factors, such as the location of the incident. Depending on the situation, the time to extinguish a fire can range from 30 minutes to 1 hour (Beneberu, 2018). This timeframe provided the basis for the heat exposure of the samples. The heat treatment was performed following the ASTM E119 (2019) standard, which defines a time-temperature curve that needs to be followed. The samples were heat treated using the following exposure times:

- 1 hr. exposure
- 30 minutes exposure

The ASTM E119 specifies temperatures that need to be reached in a certain amount of time: in 30 minutes, a temperature of 1550 degrees Fahrenheit must be reached; in 1 hour, a temperature of 1700 degrees Fahrenheit must be reached. Figure 3.16 shows the time-temperature curve specified by the ASTM code.

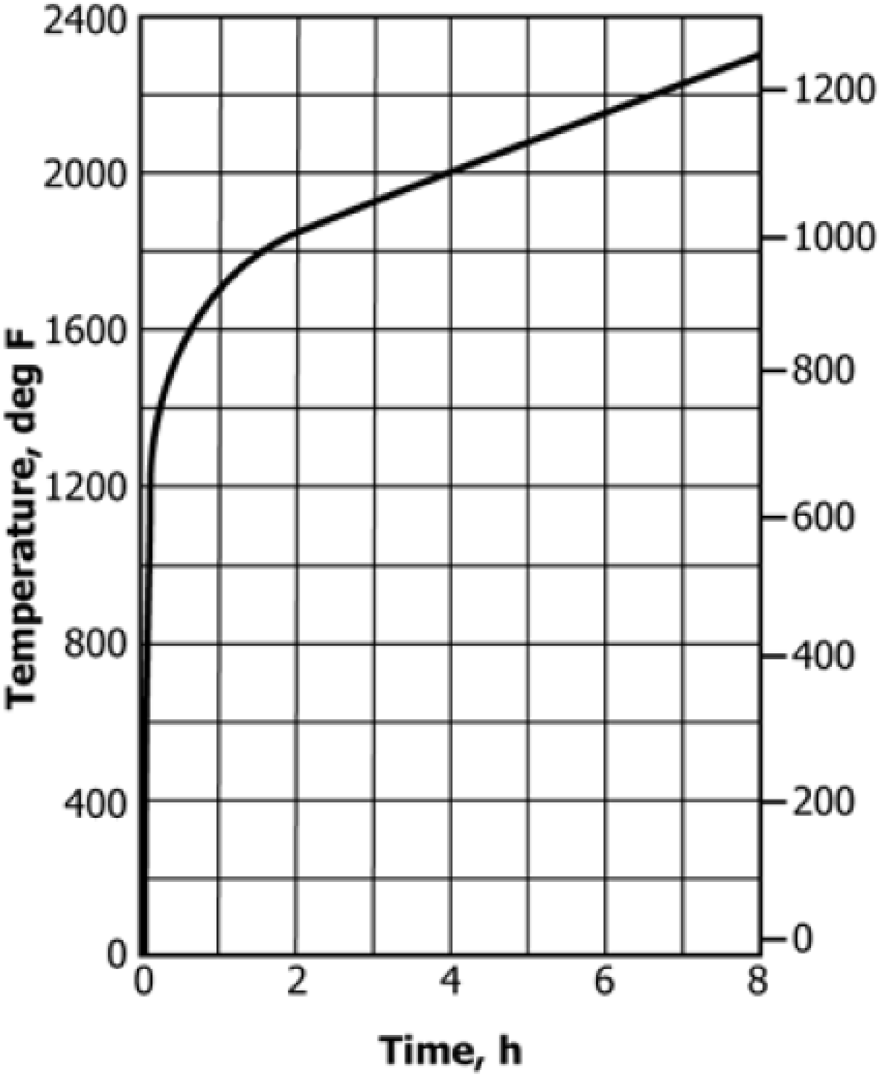


Figure 3.16 Time-Temperature Curve (ASTM 119, 2019)

An electrical furnace in the CELB was used to perform the heat treatment. The furnace is equipped with a controller that can be used to configure the temperature. The furnace's software was programmed to follow the temperature curve established by the ASTM E119 code. Table 3.6 shows the input for the temperature configuration for the 30-minute and 1-hour heat treatments.

Table 3.6 Time-Temperature Configuration

30 Minutes Heat Treatment Configuration	
Time (minutes)	Temperature (°Fahrenheit)
5	1000
10	1300
15	1399
30	1550
1 Hour Heat Treatment Configuration	
5	1000
10	1300
15	1399
30	1550
45	1638
60	1700

These values were inputted into the machine. When the heat treatment is started the furnace will try to reach those temperatures internally. Figure 3.17 shows the furnace set up.

Figure 3.17 Furnace Set Up

In order to record the exact temperatures inside the furnace, and to have a better understanding of the heat distribution on the concrete sample, three thermocouples were used for each heat treatment. One thermocouple was placed so that it touched the top surface of the beam, one was placed so that it touched the bottom surface of the beam, and the third one was embedded 4 inches into the concrete. Figure 3.18 shows the placement of the beams inside the furnace and the thermocouple set up.

Figure 3.18 Beam Set Up for Heat Treatment

After the heat treatment, the beams were taken out and seated on metal plates to cool down. Figure 3.19 shows a beam immediately after completion of the heat treatment when the furnace had been just opened.

Figure 3.19 Beam Immediately After Heat Treatment

3.5 Compressive Strength Test

The compressive test was performed following the ASTM C39 (2018) standard, using cylinders with dimensions of 4 inches diameter and 8 inches height. Following the ASTM specifications, three cylinders were casted for each sample so that an average could be obtained.

After casting, a curing compound was applied, and they were covered to prevent direct contact with the sun. Due to scheduling conflicts, the samples were tested at 90 days instead of 28 days. Prior to testing, the samples were capped with sulfur, following the ASTM C617 (2015). Figure 3.20 shows the capped samples.

Figure 3.20 Capped Cylinders

The testing was performed using a universal testing machine, in which the samples were centered and adjusted to achieve a leveled surface. Once the set up was completed, the testing was performed, with the load applied at a rate of approximately 400 pounds per second following the ASTM C39 (2018). Figure 3.21 shows the cylinder set up on the testing machine. The testing results are presented in the results sections of this report.

Figure 3.21 Compressive Test Set-up

3.6 Flexural Test

The final step of testing was the flexural test of the samples, which was performed according to the ASTM C78 specifications (2018), with a 4-point load set-up. A universal testing machine was used to perform the test. A steel beam was placed at the base of the testing machine to elevate the entire set up and was centered and leveled to ensure proper load distribution on the samples. It was marked to ensure proper placement of the bottom supports for the concrete beam, and a roller and pin support were installed. Once the beam was installed on top of the supports, two supports were installed at the top of the beam to support the load source from the machine. A roller and a pin support were placed at the top of the beam, and a small steel beam was placed on the top of these supports. This steel beam served as the support for the load cell that was installed to accurately record the load applied by the testing machine. Figure 3.22 shows the diagram of the testing set-up used in this test. Figure 3.23 shows a picture of a beam set prior to testing.

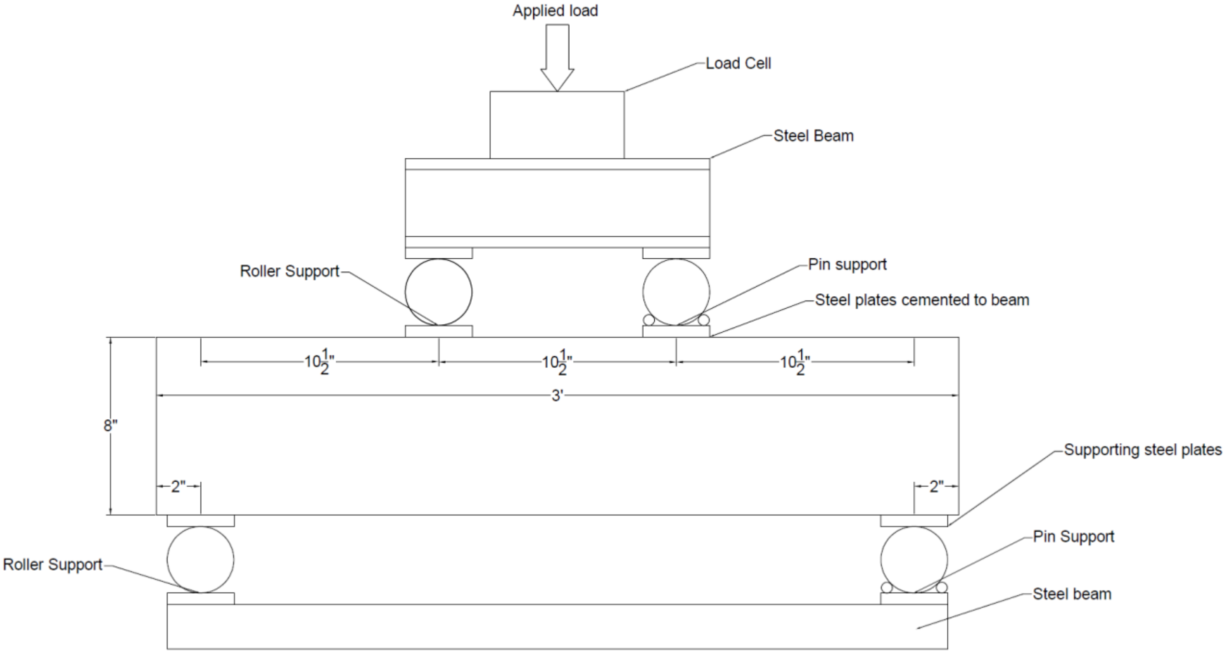


Figure 3.22 Flexural Test Set-Up Diagram

Figure 3.23 Flexural Test Set-Up with Beam

In order to accurately acquire data, several devices were installed in the beam to record measurements. Two LVDT's were installed to record deflection, one on each side of the beam, and they were attached to the steel beam which served as support for the entire set-up. The measuring ends were then adjusted so that they would touch a rigid aluminum bar that was cemented to the top of the beam. The firm attachment of the aluminum bar to the sample and the inability of the bar to deflect ensured accurate, reliable results for the beam deflection.

The strain was measured at the top and bottom of the beam, using strain gauges that were attached to the sample with a special glue. Before attaching the strain gauges to the sample, the surface was sanded and cleaned to ensure a smooth surface for better results. Figure 3.24 shows the typical placement of a strain gauge.

Figure 3.24 Strain Gauge Placement

Finally, the load was measured using a load cell that was installed at the top of the set-up. The testing machine made direct contact with the load cell. This load cell was used to have more accurate load results given that the testing machine is used by a lot of researchers and the machine might not be calibrated correctly.

All of the measuring devices were connected to a data collector. Once the set-up was complete, all the measuring devices were turned on and the data was collected while the test was running. Figure 3.25 shows all of the devices used for the flexural test. One of the LVDT's can be seen on the right side of the picture (orange device); the load cell is the orange, cylinder-shaped device at the top of the set-up; and the strain gauge cables can be seen, one going from the top of the beam and one from the bottom.

Figure 3.25 Flexural Test Measuring Devices

Chapter 4

Results and Discussion

4.1 Fresh Concrete Test Results

Several tests were performed on the fresh concrete. To ensure consistent results, the water/cement ratio was maintained at 0.51, following the proposed mix design. This was ensured by weighing the materials to be mixed in their corresponding proportions. A slump test was performed on the concrete immediately after mixing. Figure 4.1 shows the average slump results for each concrete mix.

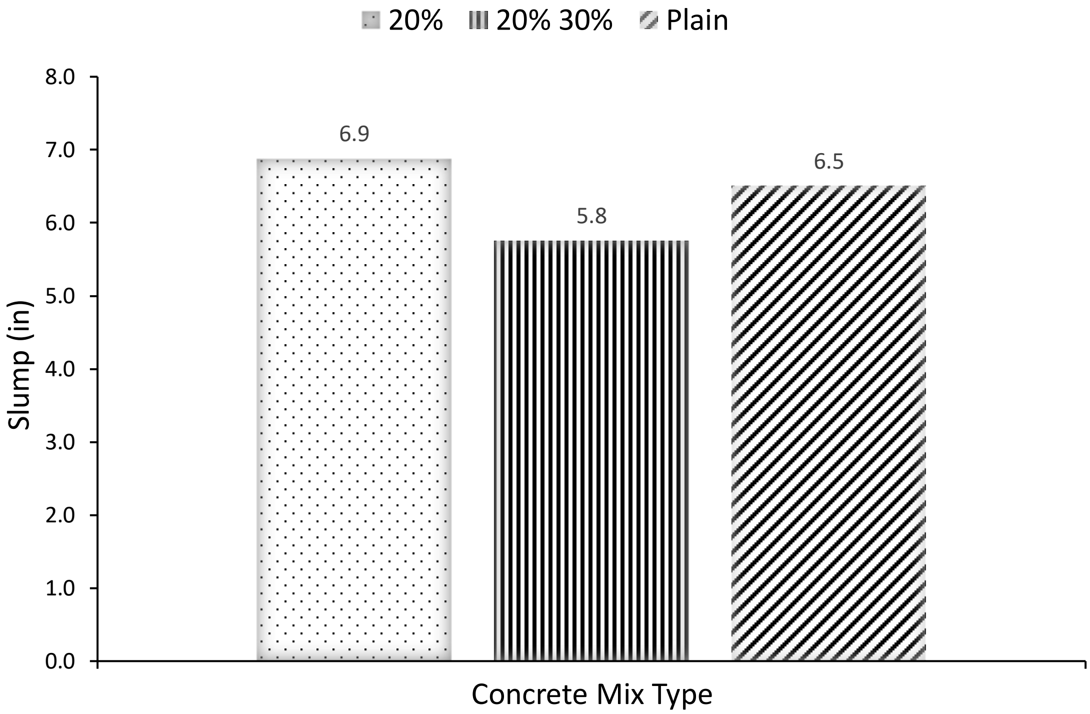


Figure 4.1 Average Slump Test Results

As can be seen in Figure 4.1, using the same water/cement ratio, the highest slump was found on the mixture with 20% VCAS as cement replacement, showing that the glass pozzolan improves the workability of concrete. This is supported by the findings of the research done by Peyvandi et al. (2013), where they reported an increase in workability of the concrete using glass powder. On the other hand, the mixture with glass pozzolan and glass aggregate had the smallest slump. This was noticed during the mixing as well, since this concrete was drier than the other mixes. Although glass doesn't absorb as much water as natural aggregates, the geometry of the glass is responsible for the reduction in workability. Additionally, since the glass comes in a wide range of sizes, with the biggest size being 5/8", the finer aggregates tend to decrease the workability of the mixtures. This is supported by the findings of the research done by Serpa et al. (2015), where they reported a decrease of workability with the incorporation of coarse glass aggregate.

A small sample of concrete was taken after mixing to be tested in the air content apparatus. After completing the entire procedure, the air content results were recorded and are summarized in Table 4.1.

Table 4.1 Air Content Test Results

Concrete Mix	Air content (%)
20% VCAS replacement	1.4
20% VCAS, 30% glass aggregate replacement	2
Plain (regular) concrete	1.8

Table 4.1 shows that the highest air content was found in the mixture that contained both glass aggregate and glass pozzolan. The lowest air content was found in the concrete that contained only glass pozzolan.

The temperature of the fresh concrete was also recorded while casting the samples. The casting was done on a warm day, with the temperatures ranging from 80 degrees Fahrenheit to 93 degrees Fahrenheit when the last concrete temperature was recorded. Table 4.2 shows the temperatures recorded for each concrete mixture.

Table 4.2 Fresh Concrete Temperature.

Concrete Mix	Temperature (°F)
20% VCAS replacement	86
20% VCAS, 30% glass aggregate replacement	91
Plain (regular) concrete	83

The concrete temperatures followed the same trend as the environmental temperature. Since the plain concrete was casted first when the morning was still cool, the concrete had the lowest temperature. The concrete with glass pozzolan and glass aggregate was casted around 3:00 pm, when the highest outside temperature was recorded as 93 °F. The high environmental temperature coincides with the highest temperature recorded on the concrete.

4.2 Compressive Strength

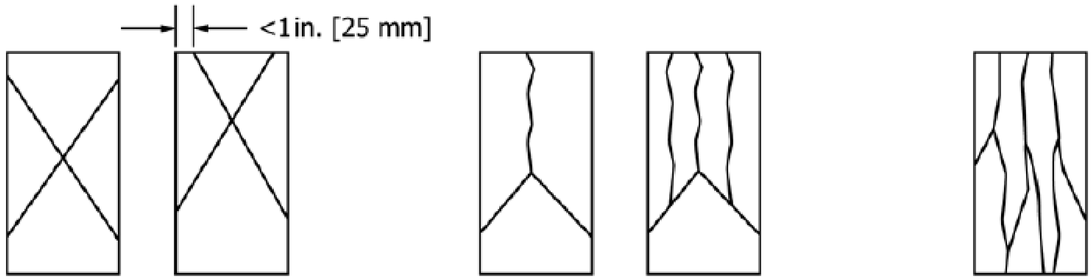
The compressive test was performed using 9 cylinders, 3 for each concrete mixture. At the beginning of the compressive testing, it was noticed that the cylinders were failing, with cracks concentrated only on one side of the sample. Two cylinders, each one of a different mix, were tested and they failed the same way. The testing machine was checked, and it was observed to be a little unleveled. It was decided to test a sample of the mix that hadn’t been tested yet to maintain the consistency of the results. After one cylinder of each mix was tested, the machine was leveled, and the rest of the cylinders were tested successfully. Figures 4.2 and 4.3 show a sample before re-leveling the testing machine and one sample after the leveling was done, respectively.

Figure 4.2 Sample Failure Before Testing Machine Readjustment

Figure 4.3 Sample Failure After Testing Machine Readjustment

Figures 4.2 and 4.3 clearly show the difference in the testing set-up. Figure 4.2 shows the failure concentrated on the top right corner of the sample. This is because the unleveled surface of the testing machine concentrated the load only on that side of the sample, making it fail prematurely. Figure 4.3 shows how the entire cylinder failed; this was because the load was applied uniformly once the testing machine was adjusted.

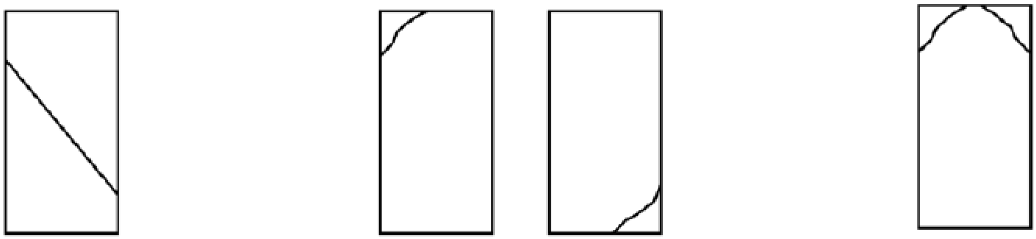
ASTM C39 (2018) presents the different types of fractures that can develop in testing cylinders. The failure modes are presented in Figure 4.4.



Type 1
Reasonably well-formed cones on both ends, less than 1 in. [25 mm] of cracking through caps

Type 2
Well-formed cone on one end, vertical cracks running through caps, no well-defined cone on other end

Type 3
Columnar vertical cracking through both ends, no well-formed cones



Type 4
Diagonal fracture with no cracking through ends; tap with hammer to distinguish from Type 1

Type 5
Side fractures at top or bottom (occur commonly with unbonded caps)

Type 6
Similar to Type 5 but end of cylinder is pointed

Figure 4.4 Schematic of Typical Fracture Patterns (ASTM C39, 2018)

Several types of fracture patterns were noticed on the testing cylinders. Plain concrete failed following the Type 2 and Type 3 patterns. Cracks appeared at the top surface and ran down to where a well-defined cone was formed. The Type 3 pattern cracks appeared at the top surface and ran down to the base, with no well-formed cones. Failed plain concrete cylinders can be seen in Figure 4.5. Only a Type 2 fracture mode was noticed for the cylinders containing 20% glass powder as cement replacement, and well-defined cones were visible at the base of the samples. A failed cylinder with a 20% glass powder replacement is shown in Figure 4.6.

Figure 4.5 Plain Concrete Fracture Patterns Type 2 (Left) and Type 3 (Right)

Figure 4.6 Concrete with 20% Glass Powder Replacement Type 2 Fracture Type

Samples containing 20% glass powder and 30% glass aggregate exhibited a different fracture pattern than the other mixes and didn't look exactly like any of the patterns shown in ASTM C39 (2018). It was a single diagonal crack that went from the top surface to the side of the cylinder, similar to the Type 4 fracture, except that the cracks began at the top surface. It was different from Type 1 as well, since no cones were formed in the fracture. Figure 4.7 shows the failure of this type of concrete.

Figure 4.7 Concrete with 20% Glass Powder and 30% Glass Aggregate Failure

The average of the three samples of each concrete mixture was used to obtain the compressive strength. The concrete mix design was done using a design strength of 3500 psi (24.13 MPa) at 28 days. Due to scheduling conflicts for the testing machine use, the testing was done at 90 days per ASTM C39 (2018). The results for this test are presented in Figure 4.8.

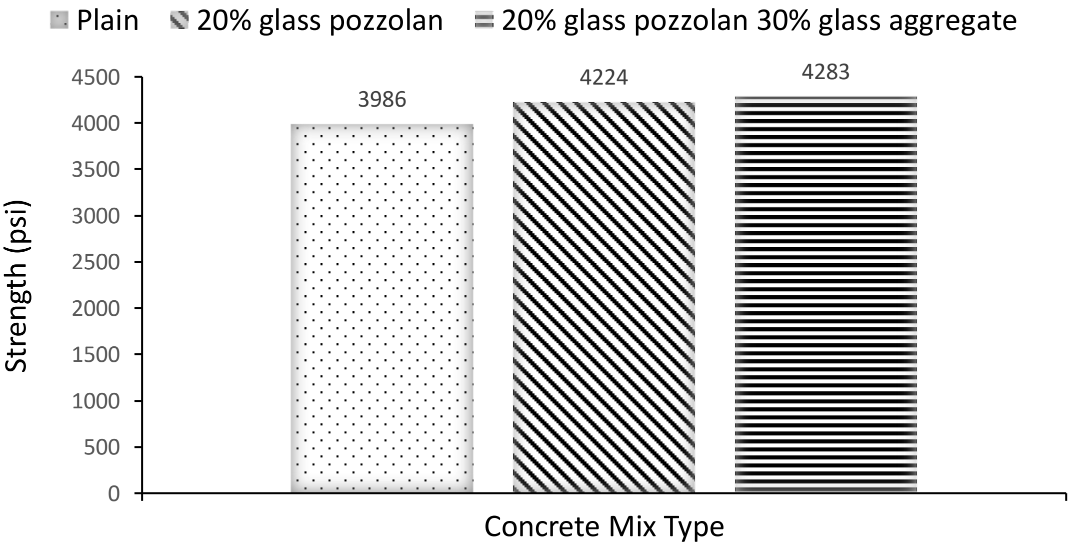


Figure 4.8 Average Compressive Strength of Concrete Mixtures

From the average of the three samples of concrete mixtures, it can be seen that glass increases the compressive strength. The samples with 20% VCAS as cement replacement and 30% glass aggregate as coarse aggregate replacement had the highest compressive strength, with 4282.68 psi (29.52 MPa) at 90 days. This supports the findings of Peyvandi et al. (2013) – that the compressive strength of concrete with glass increases more with time than regular concrete. This is true for both applications of glass. The samples that contained glass pozzolan only and the samples that contained glass pozzolan combined with glass aggregate increased by 6% and 7.45%, respectively, compared to the control samples. Note that this average is taking into account the samples that failed; however, the results show the same trend when only the samples that were tested after adjusting the testing machine were averaged. Again, the samples with glass pozzolan and glass aggregate had the highest compressive strength, whereas the regular concrete samples had the lowest value, as shown in Figure 4.9.

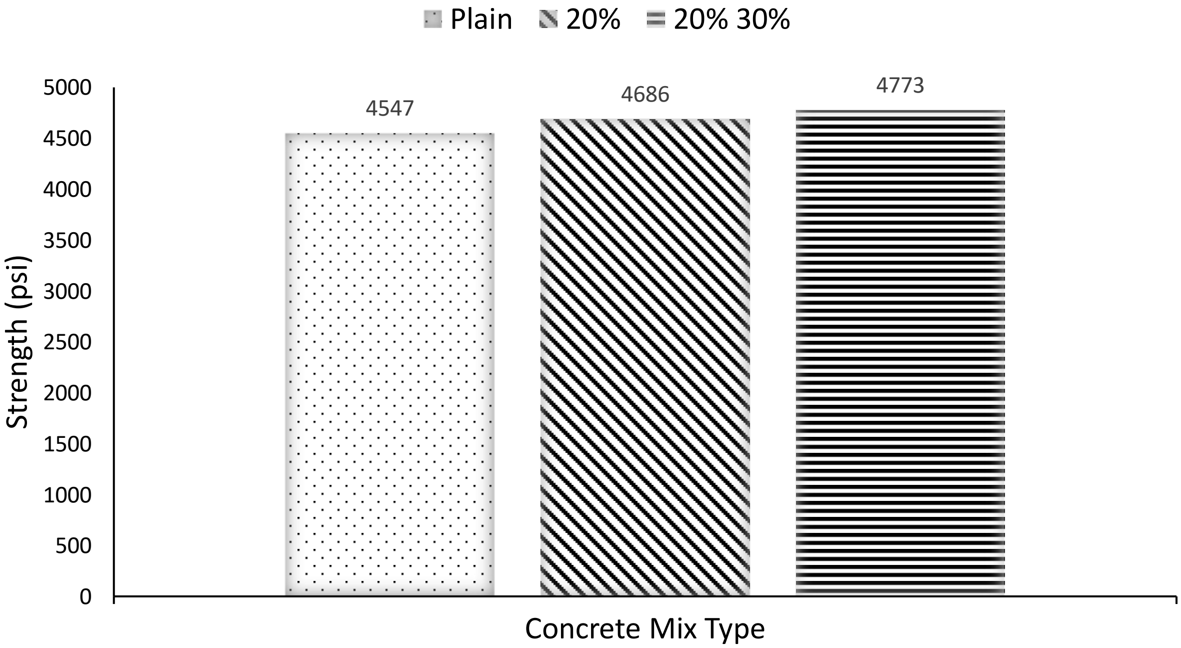


Figure 4.9 Compressive Results Using Samples After Readjustment of Testing Machine

As Figure 4.9 shows, the samples using only glass pozzolan replacement and the ones using glass pozzolan and glass aggregate had a 3% and a 5% higher compressive strength, respectively, compared to the regular concrete. Although the smooth surface of glass culets might create some concerns, the improved compressive strength comes from the sharp geometric shapes of the glass that allow better staking of the material inside concrete and results in more compact samples. These results support previous research findings. The results clearly show that glass does not negatively affect the compressive strength of concrete; on the contrary, it improves it.

4.3 Heat Treatment

The internal temperature of the samples was recorded during heat treatment to better understand the internal heat distribution since glass melts at a high temperature, and the exposure to heat might impact the mechanical properties of the glass concrete. Although, the temperature inside the furnace was set to reach 1700 °F (926 °C), the temperature inside the concrete beams did not approach the melting point of glass of 1500 °C. The temperatures recorded inside the sample is summarized in Figures 4.10, 4.11, 4.12, and 4.13. The temperature was compared at 15 minutes intervals to determine how the heat affected the samples internally after specified periods of time.

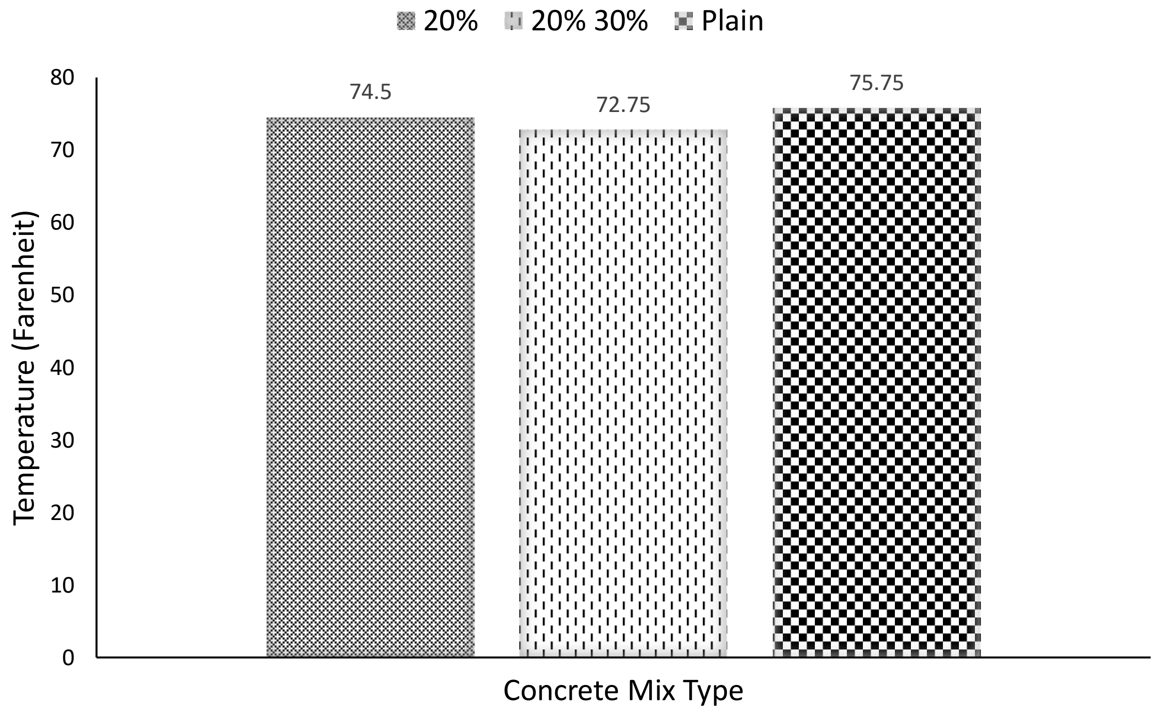


Figure 4.10 Internal Temperature After 15 Minutes

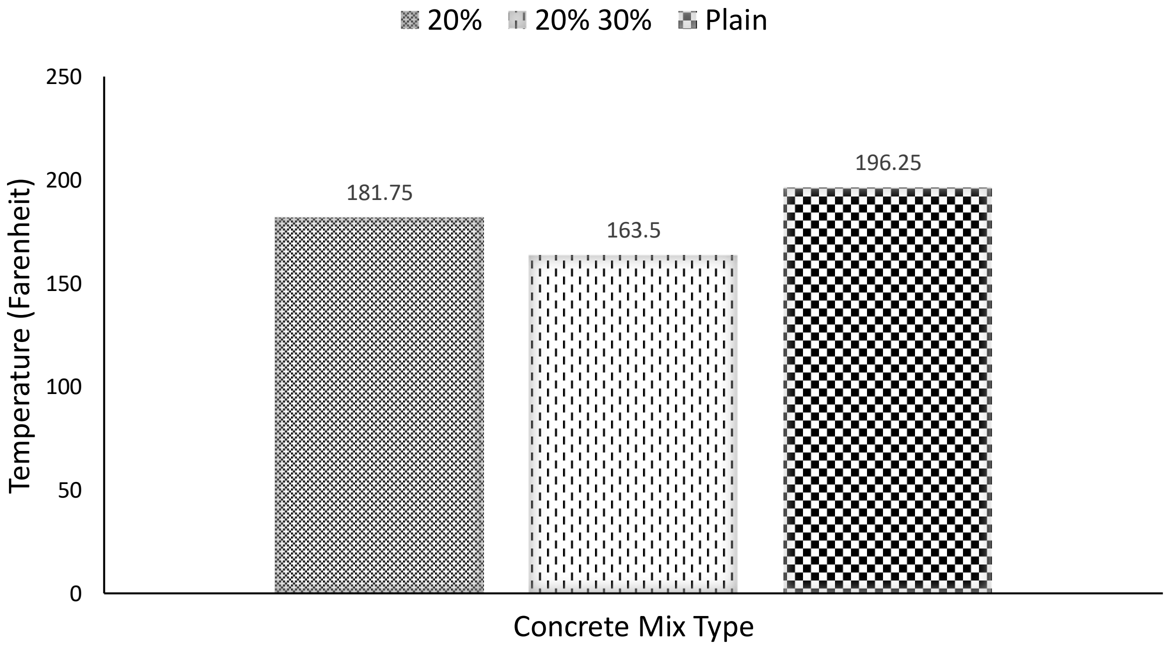


Figure 4.11 Internal Temperature After 30 Minutes

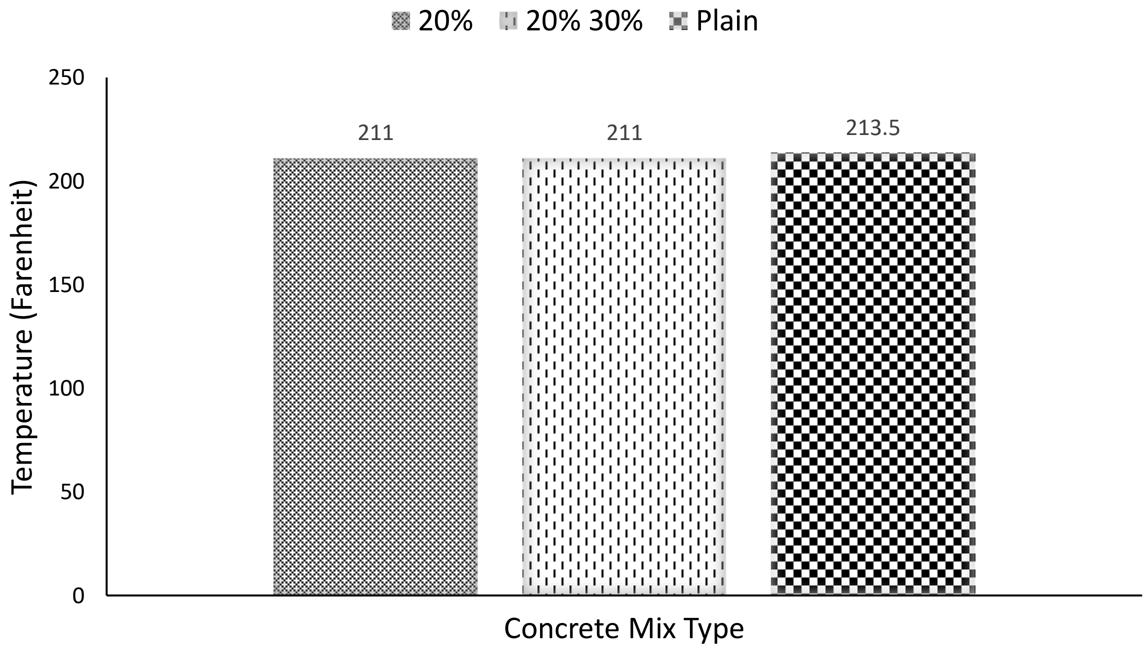


Figure 4.12 Internal Temperature After 45 Minutes

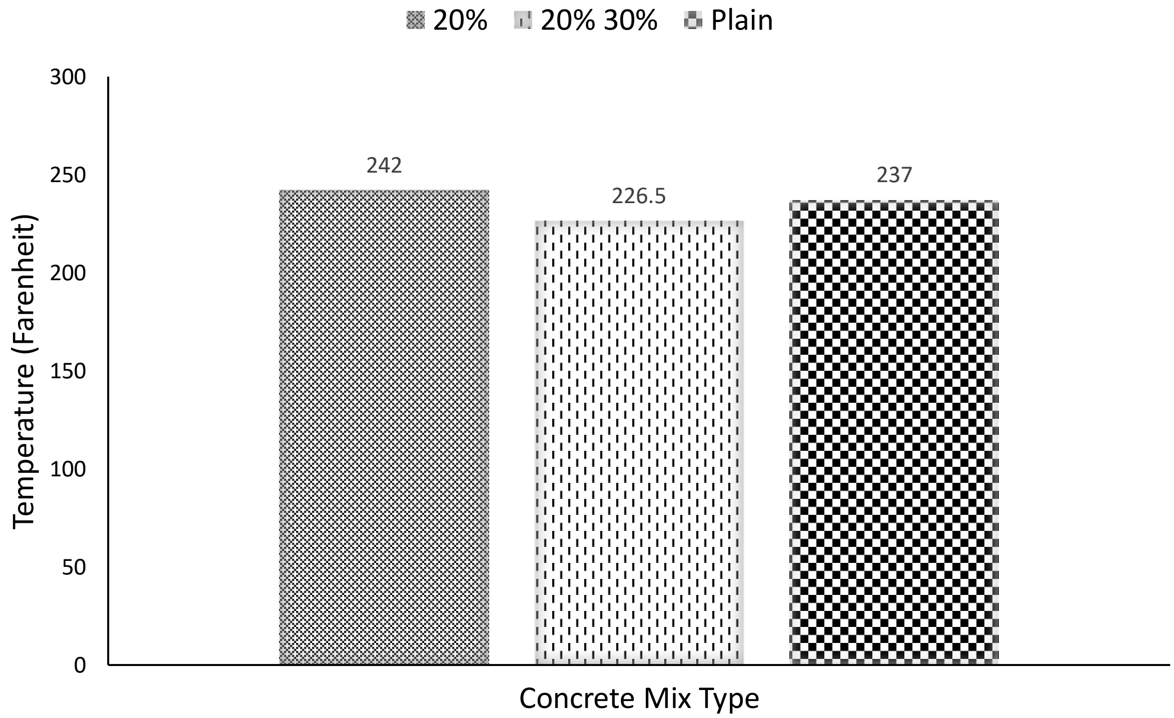


Figure 4.13 Internal Temperature After 1 Hour

The beams made of conventional concrete reached higher temperatures during the first 45 minutes of heat treatment. The biggest difference can be seen during the first 30 minutes of exposure, when the internal temperature of the plain concrete was 15°F higher than the other samples. During the first 45 minutes of heat treatment, the samples of glass concrete showed a lower internal temperature, as if the glass worked as an insulator. After 45 minutes, however, the beams containing only glass pozzolan as cement replacement showed a steep increase in temperature, which led to it having the highest internal temperature of the three mixtures. The beams containing glass pozzolan and glass aggregate always showed the lowest internal temperature, which indicates a positive effect of the glass culets on the temperature distribution. The air content test also showed more air in the concrete with glass pozzolan and glass culets, which may be why this type of concrete did not heat up as much as the other mixes. The additional air and the glass culets that were present did not affect the compressive strength of the concrete. The glass seems to function as an insulator inside the material, while maintaining an acceptable and improved strength capacity.

The results of the heat treatment tests are summarized in Figure 4.14 and depict the trend of the internal temperatures during the entire treatment. The temperatures of the samples containing the same type of mix were taken at one-minute intervals, averaged, an inputted into a graph. A jump in the temperature can be seen in all of the samples after 30 minutes.

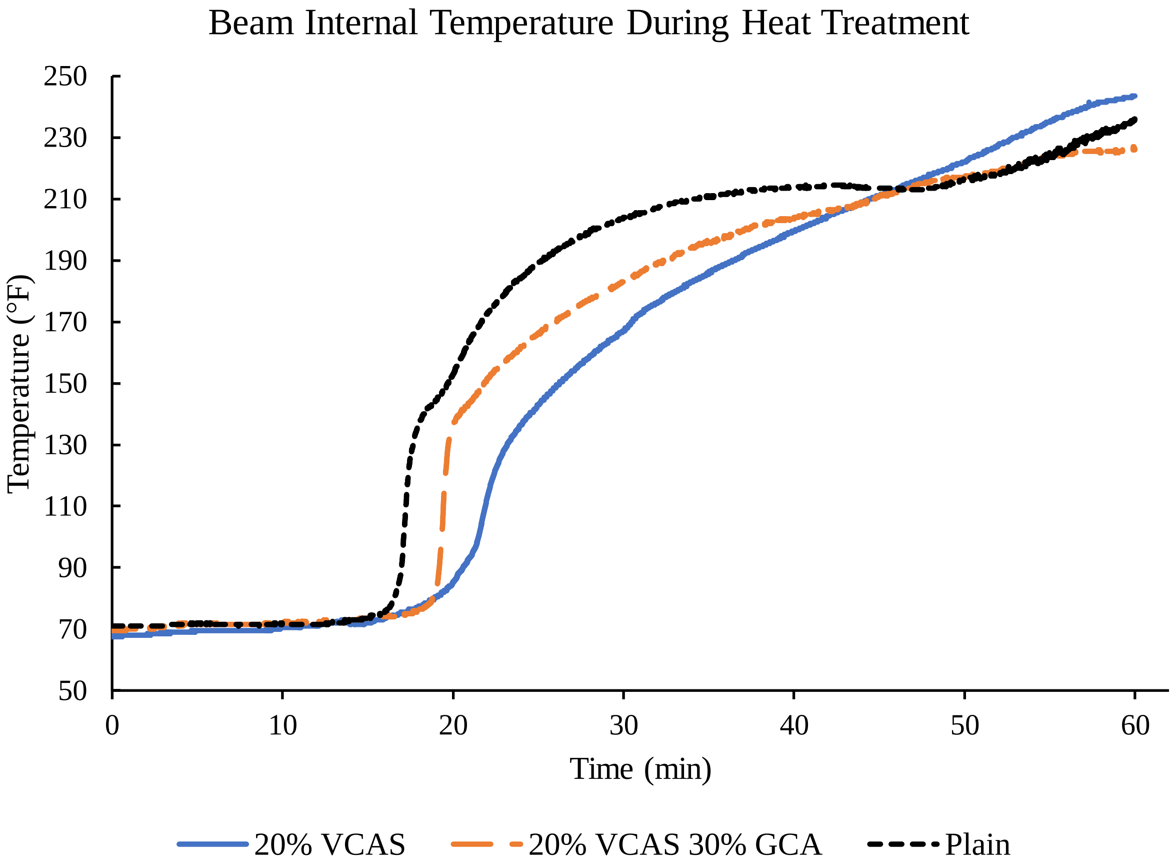


Figure 4.14 Average Internal Temperatures of Beams.

Pictures of the beams were taken after the heat treatment, and the beams exposed to heat for 30 minutes only showed very small cracks that developed while the beams were cooling down, not during the heat treatment itself. The beams exposed to 1 hr. of heat treatment had a lot more surface damage. As it can be seen in the following figures, no damage was seen immediately after the exposure to heat, but it developed during the cooling down period. Although the samples with 20% glass pozzolan showed a higher internal temperature, the surface damage was less than that of the other concrete mixes. This indicates a better material resistance to heat, even though more heat was transferred inside the sample. Additionally, a change in color was noticeable on the different kinds of concrete mixes. The beams after heat exposure can be seen in figures 4.15, 4.16, 4.17 and 4.18.

Figure 4.15 Samples with 20% Glass Pozzolan Exposed to Heat for 30 Minutes (Left) and Samples Exposed to Heat for 1 Hour (Right)

Figure 4.16 Samples with 20% Glass Pozzolan and 30% Glass Aggregate Exposed to Heat for 30 Minutes (Left) and Samples Exposed to Heat for 1 Hour (Right)

Figure 4.17 Samples with Regular Concrete Exposed to Heat for 30 Minutes (Left) and Samples Exposed to Heat for 1 Hour (Right)

Figure 4.18 Damage of Sample with Regular Concrete After Heat Treatment

As mentioned before, the samples with only 20% glass pozzolan were less damaged by the heat, even though they showed a higher internal temperature. As Figure 4.18 shows, the beams made of regular concrete had more surface damage, especially at the edges, and the damage became more apparent with time. The image in Figure 4.17 was taken a few days after the image in Figure 4.18, and a lot more damage is visible.

4.4 Flexural Load

The flexural testing of the unreinforced beams was performed using the third point load method per ASTM C78. Although concrete itself has very little tensile strength, the test was designed to see how the glass components affect the concrete's flexural behavior.

A total of 18 beams were tested. Six beams were exposed to heat for 30 minutes, 6 beams were exposed to heat for 1 hour, and six beams were tested without exposure to heat. The beams with no fire exposure were tested first. Figure 4.19 shows the maximum load carried for each beam. Figure 4.20 shows the average maximum load for each type of mixture.

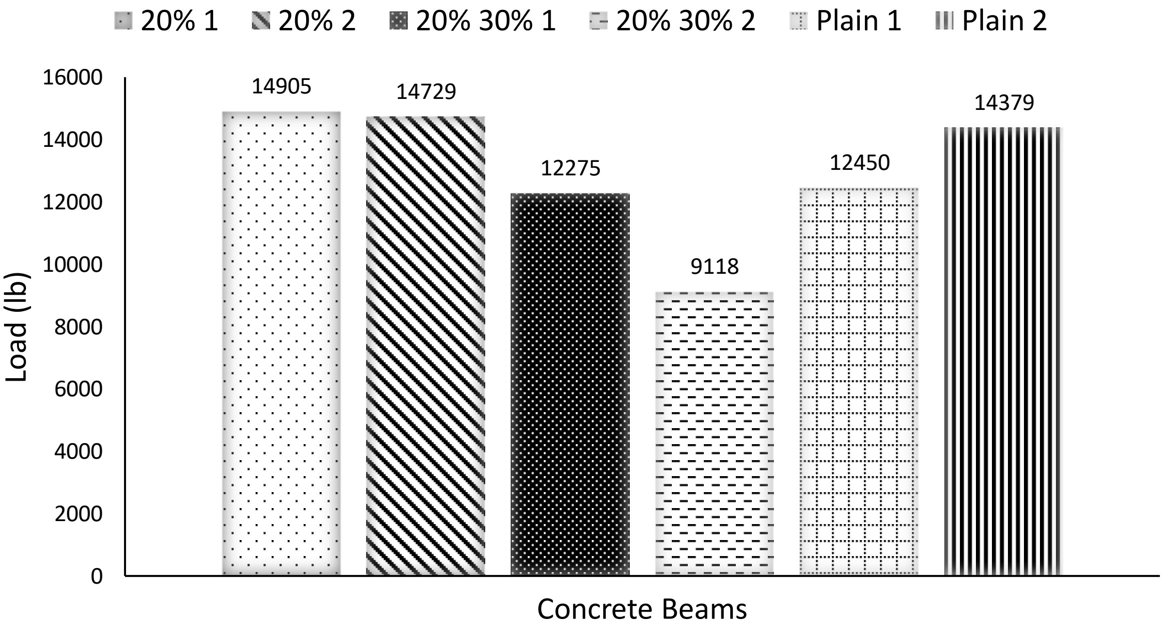


Figure 4.19 Flexural Load Results of Beams with No Fire Exposure

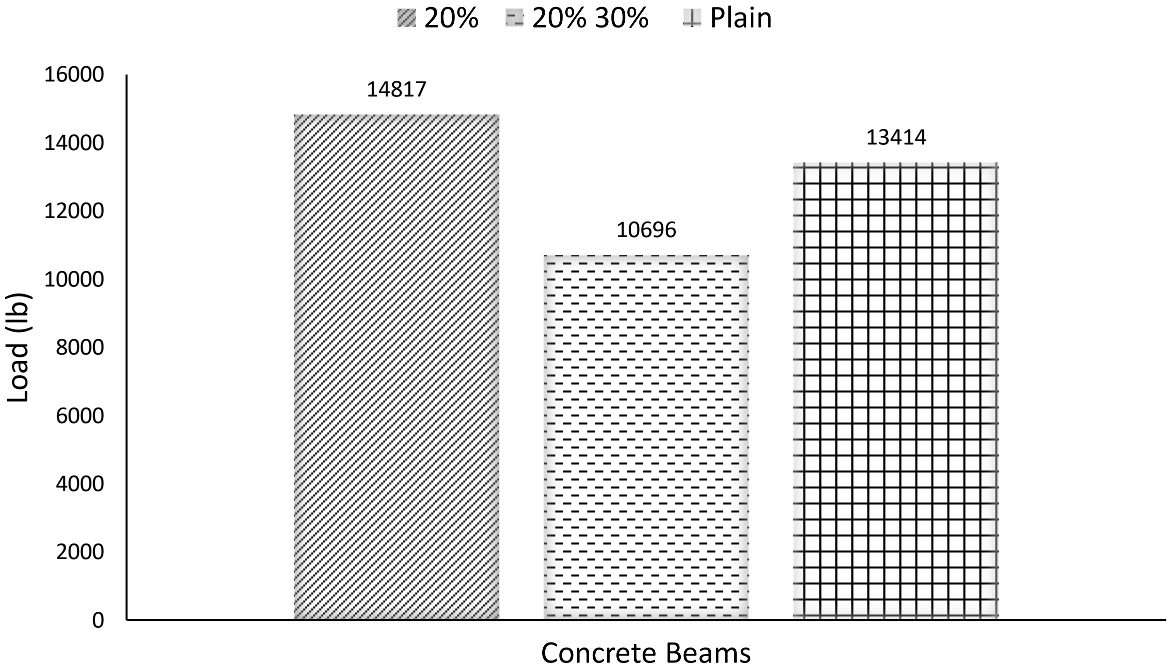


Figure 4.20 Average Flexural Load Results of Beams with No Heat Exposure

Figures 4.19 and 4.20 show a comparison of the load capacity of the beams. It can be seen that beams containing glass aggregate and glass pozzolan had the lowest strength, with an average of 10696.41 lb. (47.58 KN). This was due to the smooth surface of the glass culets, which affected the bonding of the material to the concrete. Ironically, the material with the greatest compressive strength was the weakest in respect to flexural capacity. This contradiction infers that the smooth surface of glass does not affect the compressive behavior. When tensile stress is present, however, although a better internal stacking of material can be achieved, the smooth surface of the glass affects the bonding of the materials and decreases the tensile capacity of the beams at regular temperature. On the other hand, when only glass pozzolan is added, the flexural capacity increases. The results showed that this type of mixture had the highest load capacity, at 14817 lbs. (65.9 KN), which is a 10% strength increase over the regular concrete load capacity.

As expected, the sudden failure of the beams was brittle, and began with a crack appearing in the center of the beam, as shown in Figure 4.21.

Figure 4.21 Typical Beam Failure with No Heat Exposure

The beams exposed to 30 minutes of heat treatment showed a significantly greater loss of load capacity than the beams with no fire exposure. One of the samples with 20% glass powder and 30% glass aggregate failed right before testing started, so no data was acquired for it. For this type of mixture only one sample was considered. The results for each sample are shown in Figure 4.22; the average results for each type of mixture are presented in Figure 4.23.

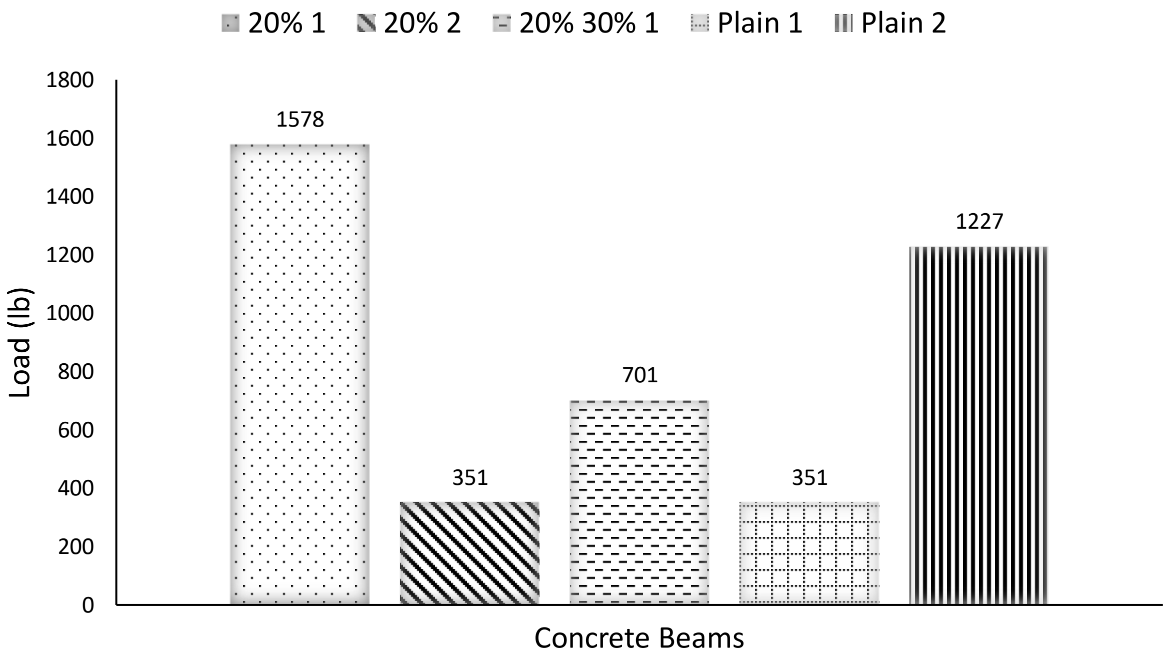


Figure 4.22 Flexural Load Results of Beams with 30 Minutes Heat Exposure

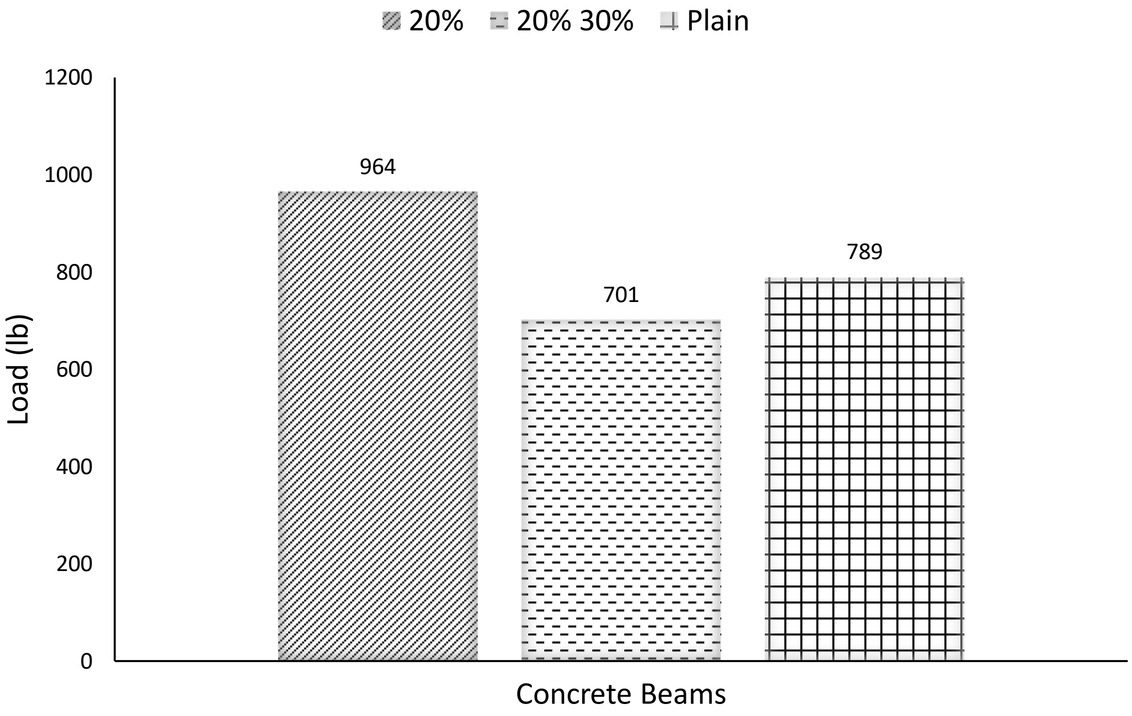


Figure 4.23 Average Flexural Load Results of Beams with 30 Minutes Heat Exposure

The load results followed the same trend as the beams with no heat exposure. The beams with only glass pozzolan had the highest load capacity, with 964lbs. (4.2 KN). A significant loss of load capacity was seen after 30 minutes of heat exposure, and a decrease of 93% strength was seen on the 20% glass pozzolan samples, which were the samples with the highest strength. The sample with glass aggregate and glass pozzolan was again the weakest, with only 701lbs. (3.1 KN).

The expected brittle failure did not occur in the samples with glass components. Instead, the failure was ductile, with cracks appearing on the samples (Figure 4.4.6.) This was an unexpected outcome of the test since no reinforcement was provided. Although the capacity decreased, the samples developed cracks before failing. This effect was not noticed on the plain concrete samples since they failed through the middle, similar to the samples with no heat treatment. This indicates that because glass melts, it becomes more ductile after it is exposed to fire. The samples containing only glass powder gained ductility while maintaining the highest load capacity.

Figure 4.24 shows the cracks that developed on one of the beams that was exposed to heat for 30 minutes.

Figure 4.24 Cracks Developed on Beams with Glass Components with 30 Minutes Heat Treatment

The beams that were heat treated for one hour showed a greater load capacity reduction than the previously tested beams. The beams made with regular concrete showed no load resistance at all, as they were not strong enough to carry their own weight and failed in place due to the large cracks that developed through the middle. One of the beams broke when it was lifted; another beam was left in place. The beams made of regular concrete were more damaged after heat treatment, even though their internal temperature was not the highest. This was proven after the beams failed. Figure 4.25 shows the failed beams.

Figure 4.25 Failed Beams Before Testing

Figure 4.26 shows the results of the flexural test. Figure 4.27 shows the average load for each type of mixture.

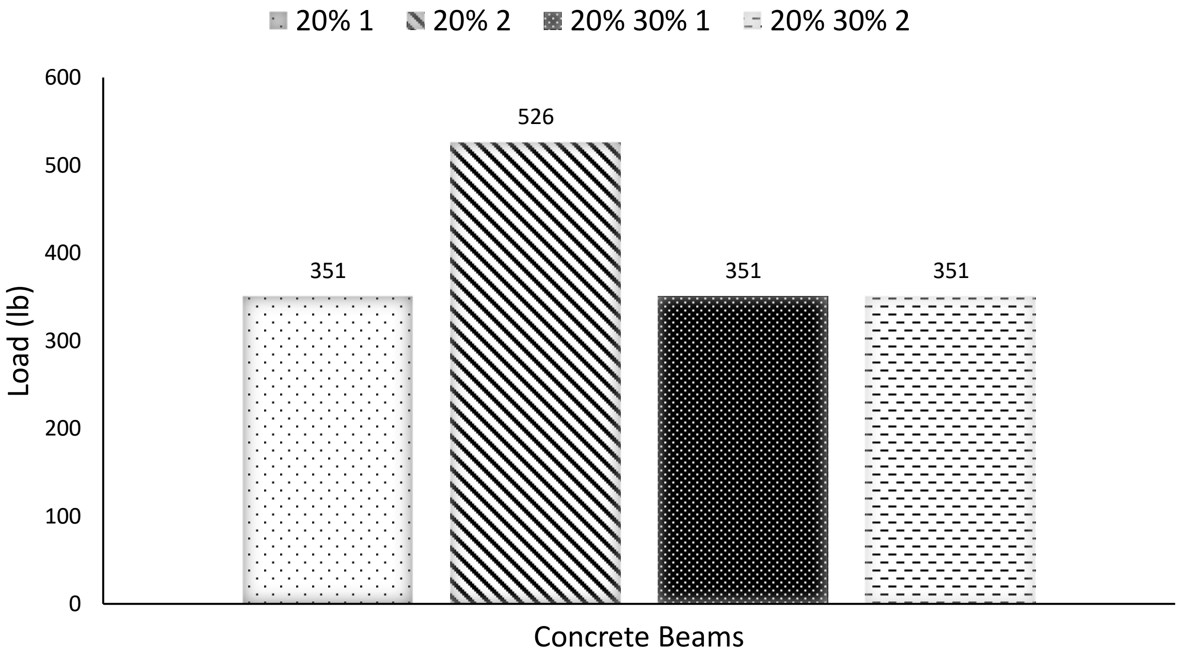


Figure 4.26 Flexural Load Results of Beams with 1-Hour Heat Exposure

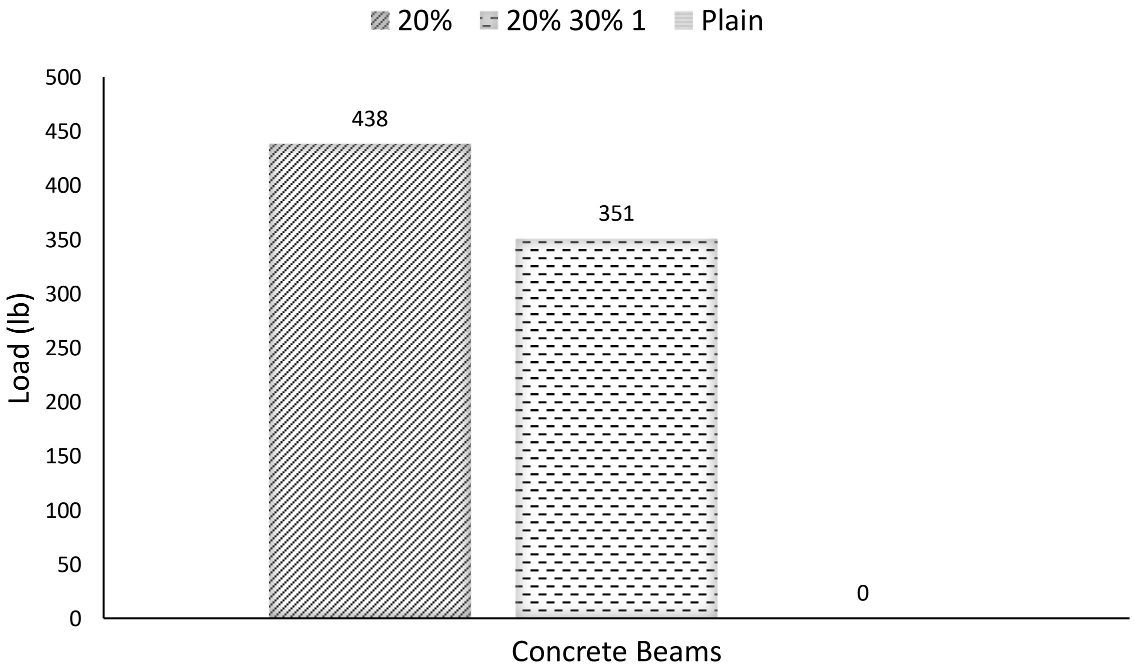


Figure 4.27 Average Flexural Load Results of Beams with 1-Hour Heat Exposure

Since the samples made with regular concrete failed before any testing could be done, no data is available for them. For the analysis, a load capacity of 0 lbs. was considered. As in the previous cases, the samples with 20% glass pozzolan showed the highest load capacity, with an average load of 438 lbs. (1.9 KN). For the samples with 20% glass pozzolan and 30% glass aggregate, the average load capacity was 350 lbs. (1.5 KN). It should be noted that the load for both the 20% glass pozzolan and 30% glass aggregate beams was 350 lbs. This is because the beams were so weak that they failed as soon as the testing machine began to apply the load. The load cell was able to quickly record a few load values, the maximum of which was 350 lbs. These tests provided little data but was enough to provide a visualization of the main idea of the project. Although, the samples had extensive fire damage and the concrete had almost no load resistance, adding glass to the mixture benefitted the mechanical performance compared to the regular concrete, which demonstrated no load capacity at all.

The failure of the beams heat treated for one hour was brittle and they failed as soon as the load began to be applied. They did not fail through the middle as before, however, but failed at the points of supports, breaking the beam into three almost equal pieces, indicating an enormous loss of strength. One of the failed beams can be seen in Figure 4.28.

Figure 4.28 Typical Beam Failure After 1-Hour Heat Treatment

Load versus strain and load versus displacement graphs were developed for the strongest beam of each category to better understand the flexural behavior of the different types of concrete. The raw data was modified, using the moving average of the data points to plot the graphs, and the unit interval changed, depending on the exposure to fire. Since fire affected the load capacity of the beams, few data points were acquired for the beams exposed to fire for 30 minutes 1 hour. The interval for the beams with no fire exposure was 10, and the interval for beams with 30 minutes exposure was 100. Since the beams with 1-hour of fire exposure had very few data points, a unit interval of 3 was used. The strain versus load and strain versus displacement graphs for the beams with no fire exposure are presented in figures 4.29, 4.30, 4.31, 4.32, 4.33 and 4.34.

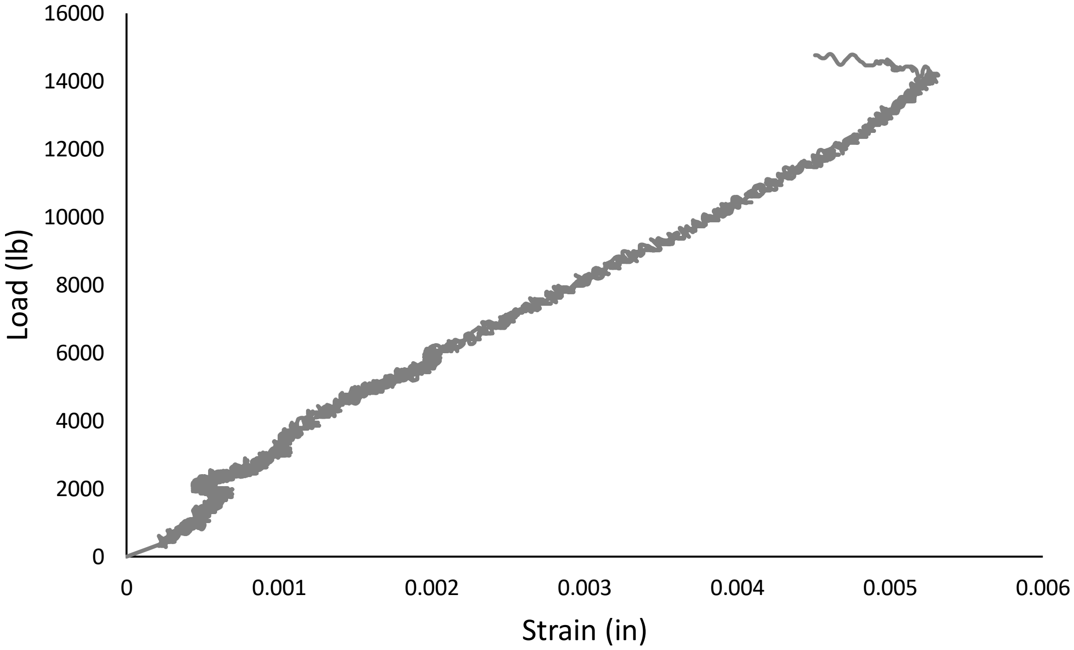


Figure 4.29 Load vs. Strain for Beam with 20% Glass Powder with No Heat Treatment

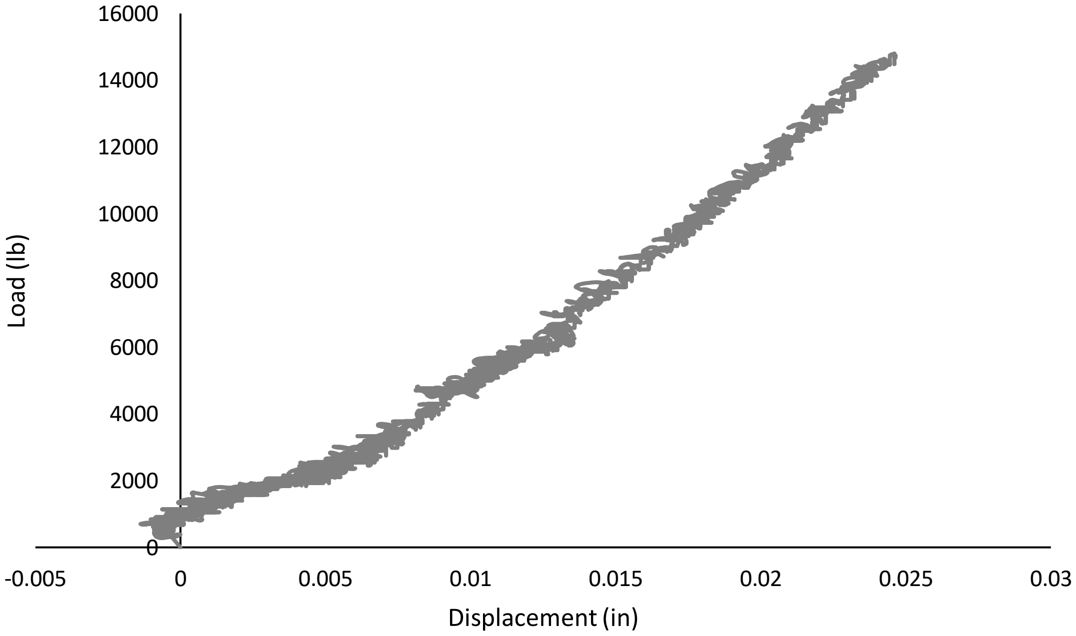


Figure 4.30 Load vs. Displacement for Beam with 20% Glass Powder with No Heat Treatment

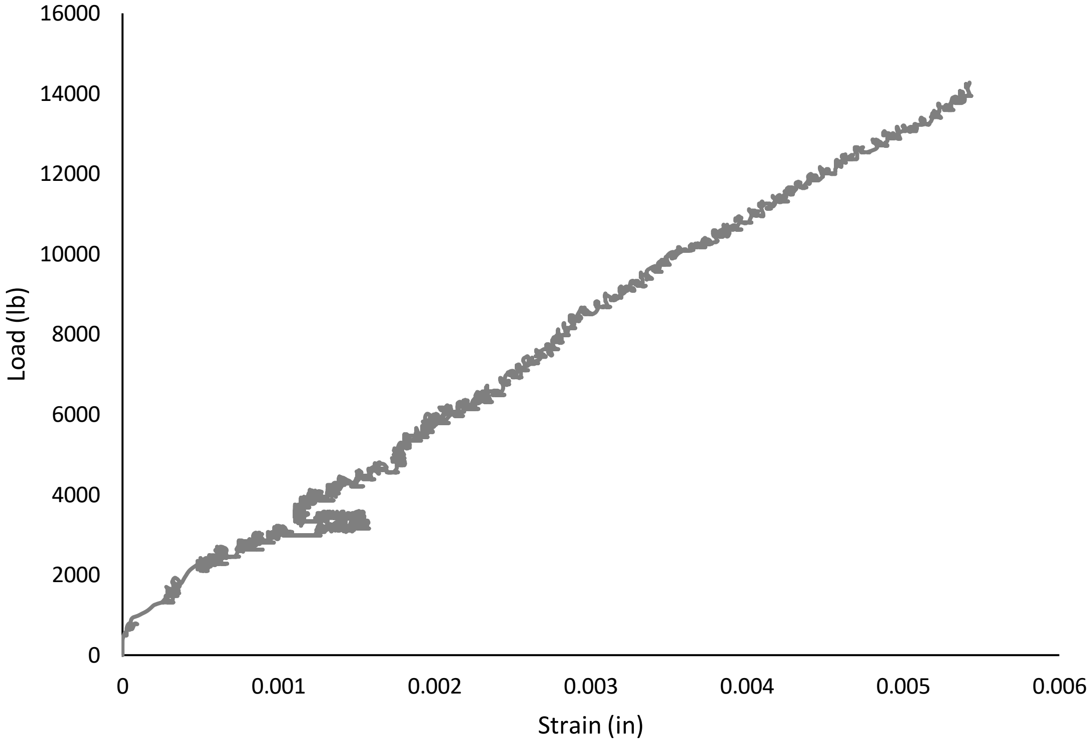


Figure 4.31 Load vs. Strain for Beam with Plain Concrete with No Heat Treatment

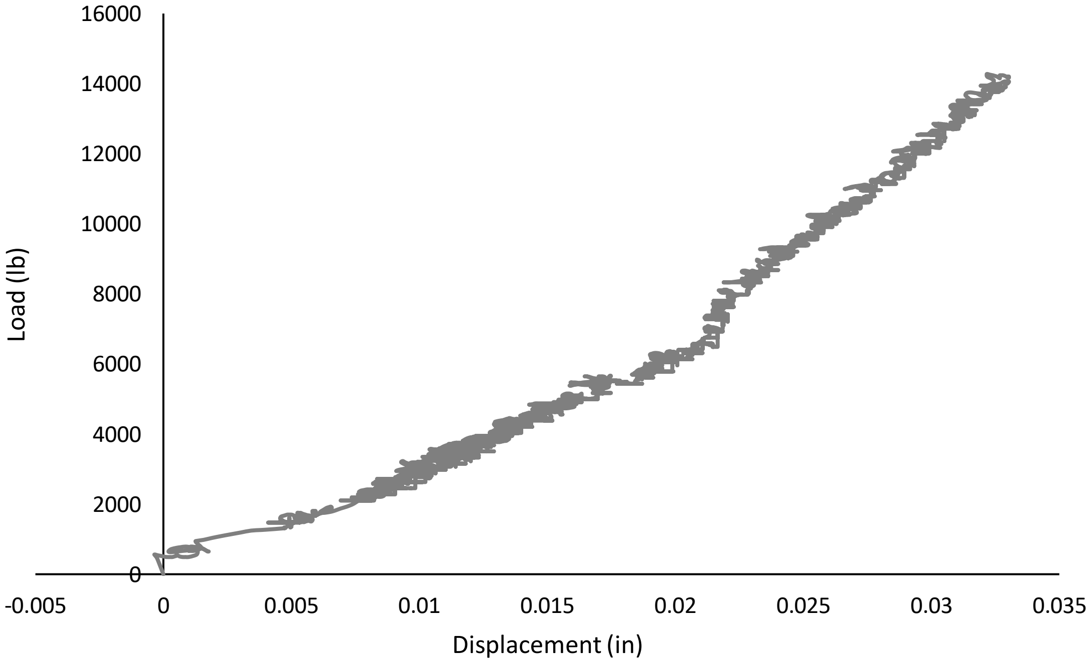


Figure 4.32 Load vs. Displacement for Beam with Plain Concrete with No Heat Treatment

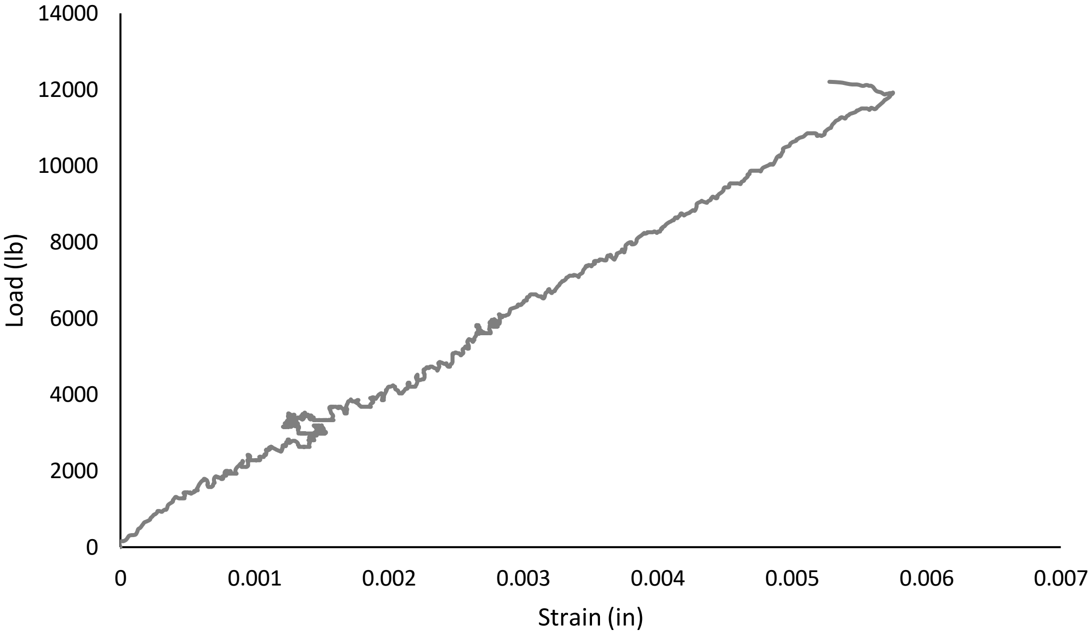


Figure 4.33 Load vs. Strain for Beam with 20% Glass Powder and 30% Glass Aggregate with No Heat Treatment

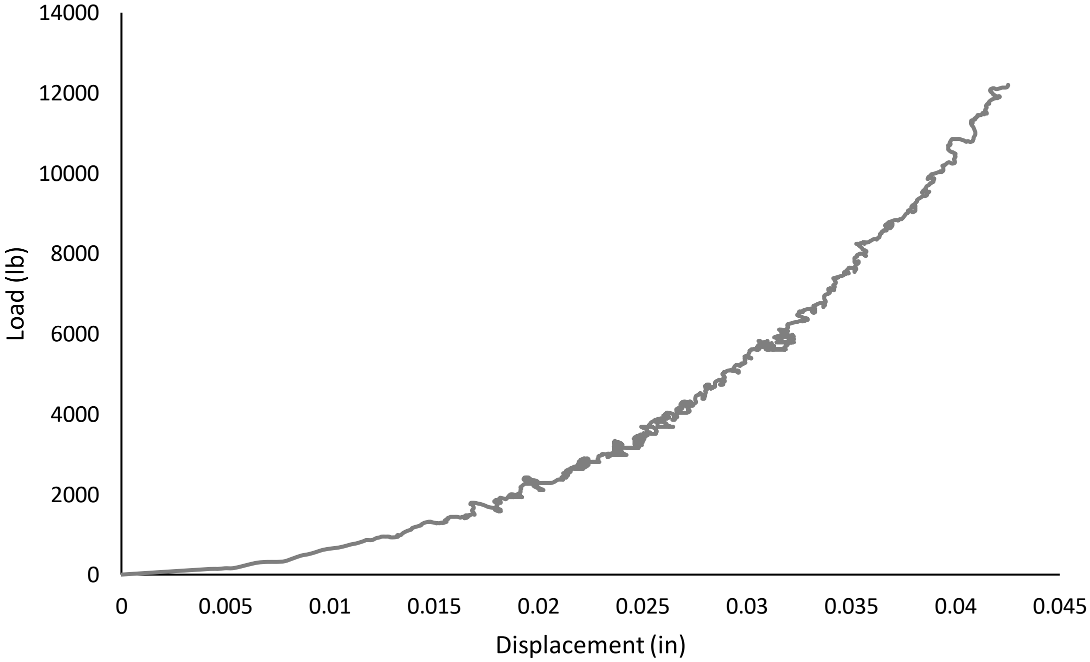


Figure 4.34 Load vs. Displacement for Beam with 20% Glass Powder and 30% Glass Aggregate with No Heat Treatment

As can be seen, all of the samples had a strain of approximately 0.005 in (140 µm) at the time of failure. The sample with the largest strain was the beam containing glass powder and glass aggregate. This sample is also the one with the lowest load capacity compared to the other mixes. Similarly, this sample showed the largest displacement, exceeding 0.04 in (1.016 mm). The concrete with glass powder and glass aggregate became more elastic compared to the other two mixes. On the other hand, although this type of concrete had the highest load capacity, the samples containing only 20% glass powder as cement replacement showed the lowest strain and displacement.

Similar graphs were generated for the beams with 30 minutes heat exposure. As mentioned before, the data was arranged using a moving average of 100 units. The strain versus load and strain versus displacement graphs for the beams with 30 minutes fire exposure are presented in figures 4.35, 4.36, 4.37, 4.38, 4.39 and 4.40.

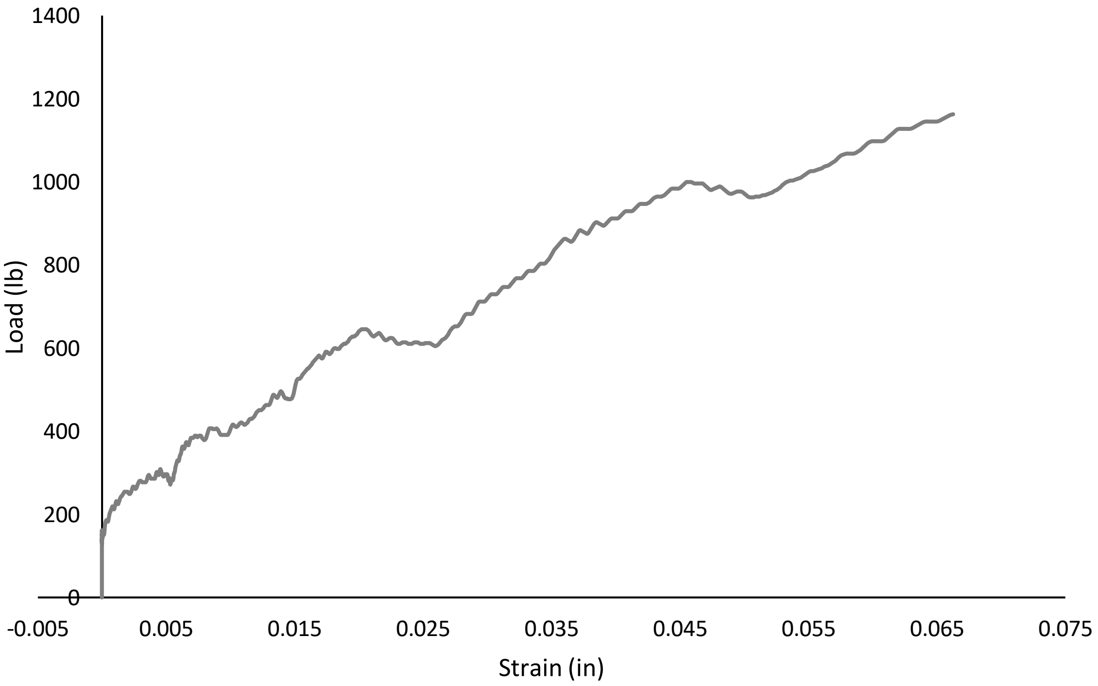


Figure 4.35 Load vs. Strain for Beam with 20% Glass Powder with 30 Minutes Heat Treatment

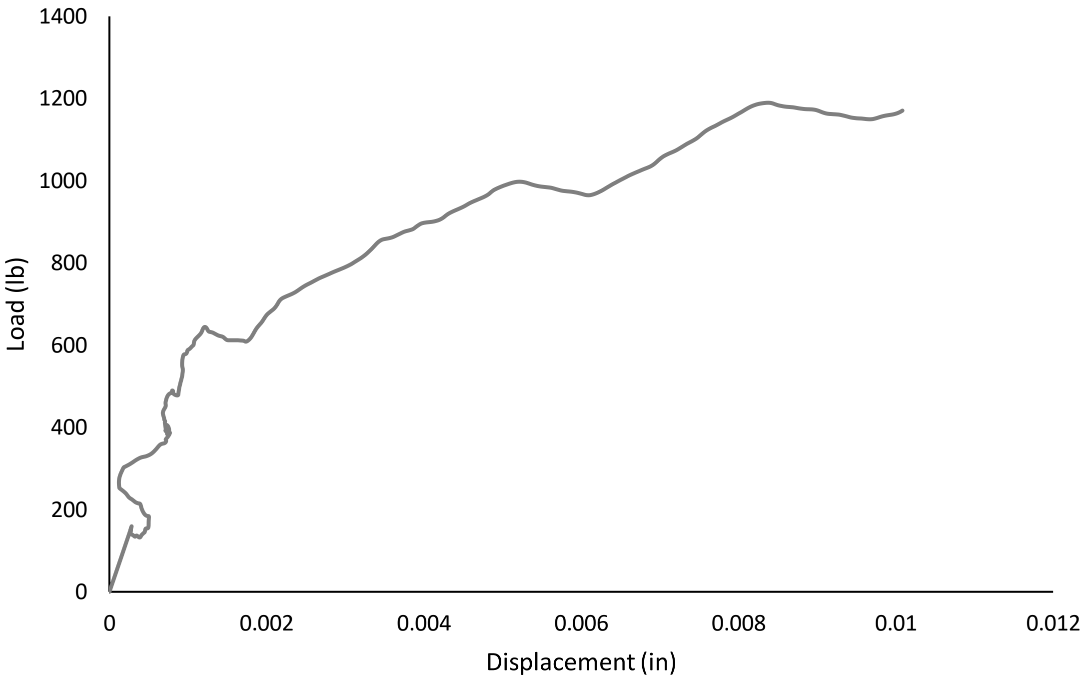


Figure 4.36 Load vs. Displacement for Beam with 20% Glass Powder with 30 Minutes Heat Treatment

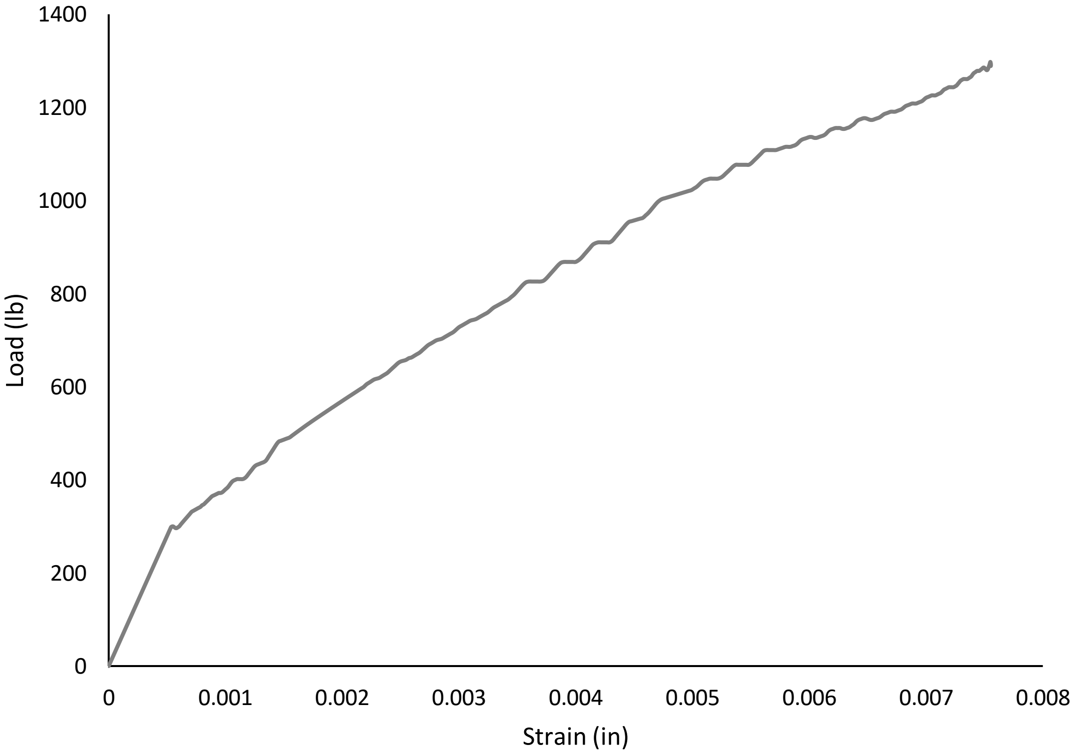


Figure 4.37 Load vs. Strain for Beam with Plain Concrete with 30 Minutes Heat Treatment

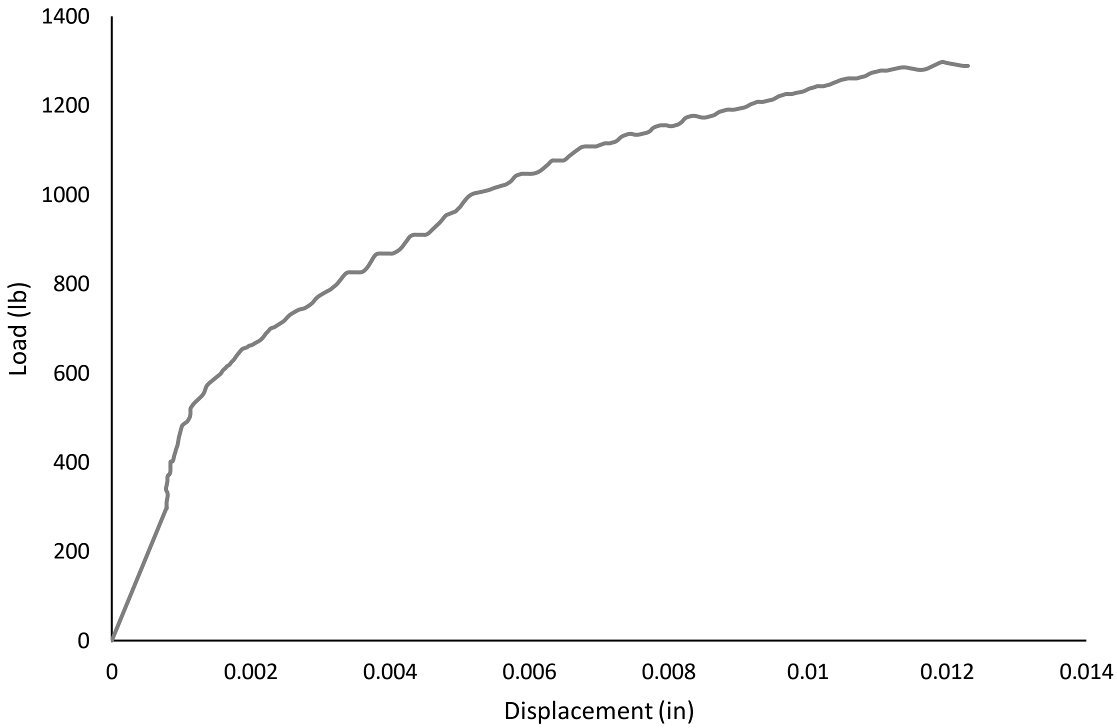


Figure 4.38 Load vs. Displacement for Beam with Plain Concrete with 30 Minutes Heat Treatment

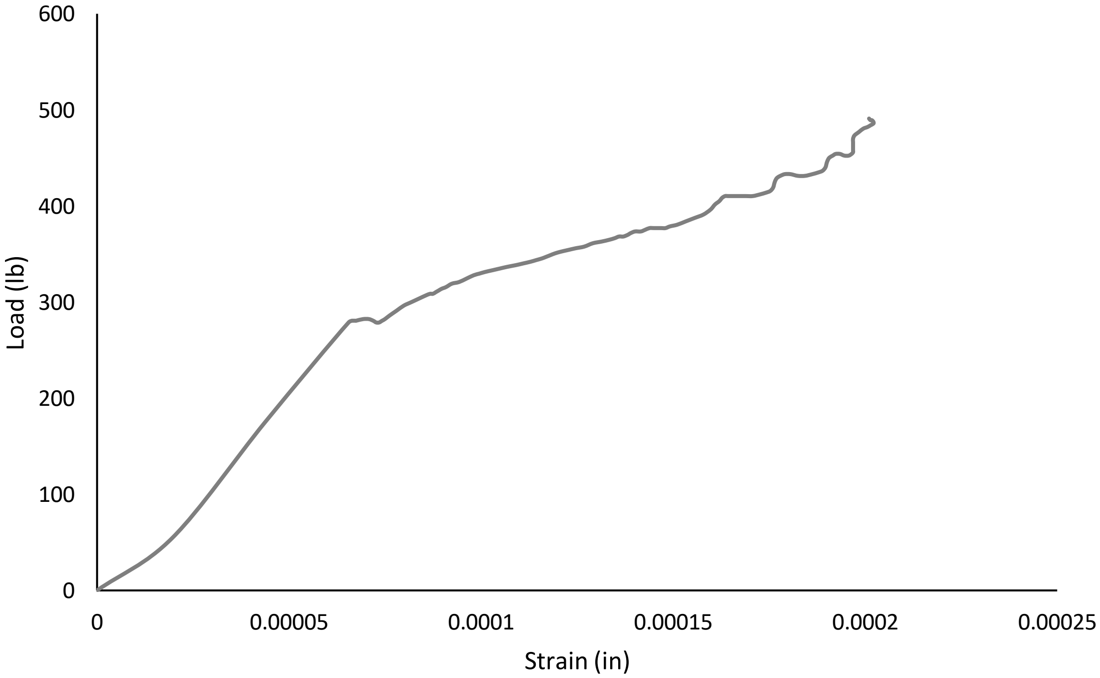


Figure 4.39 Load vs. Strain for Beam with 20% Glass Powder and 30% Glass Aggregate with 30 Minutes Heat Treatment

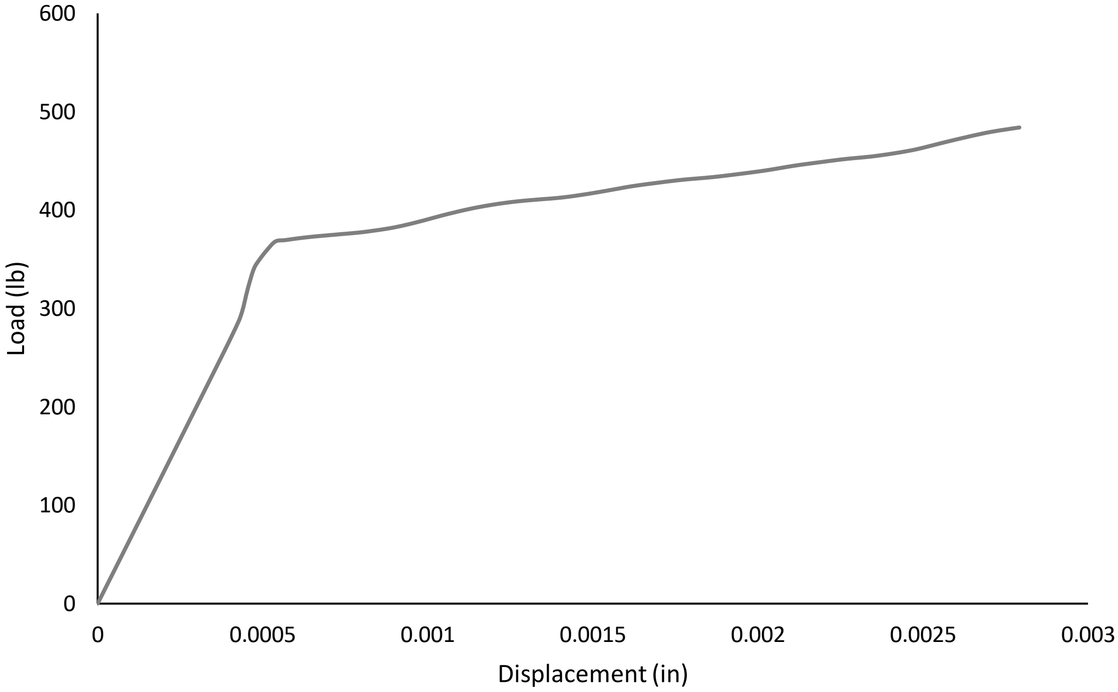


Figure 4.40 Load vs. Displacement for Beam with 20% Glass Powder and 30% Glass Aggregate with 30 Minutes Heat Treatment

The graphs for the beams with 30 minutes heat treatment showed different results for each type of mixture. The beams with only 20% glass powder showed a significant increase in the strain compared to the beams with no heat exposure. On the other hand, the beam with 20% glass powder and 30% glass aggregate showed a reduction in the strain compared to the beam with no heat treatment. The beam with plain concrete showed similar results to the plain concrete beam with no heat treatment. Regarding displacement, the 20% glass powder and the plain concrete beams showed similar results of about 0.01 inches (.25 mm). The displacement of the 20% glass powder and 30% glass aggregate sample was lower than the other samples with only 0.003 inches (0.07 mm).

The graphs for the beams with 1-hour heat exposure were developed. Since the beams failed as soon as the testing machine started applying load, only a few data points were taken. Due to the small amount of data acquired during this test, the graphs do not show their typical curve pattern. Thus, it was decided that the graphs did not show relevant information, so they are not shown on this paper. However, it was noticed that an overall reduction of the strain and the displacement was seen on this kind of samples when compared to samples with less heat exposure.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

After sample preparation, testing performance, and result analysis, the following conclusions can be made about the effects glass components in concrete:

- The use of glass aggregates and glass pozzolan can increase the compressive strength of concrete by 5%. This strength is gained overtime as suggested by previous research projects.
- Glass aggregates can help reduce the internal temperature of concrete. It has an insulating effect compared to regular concrete.
- Glass aggregate affects the flexural capacity of concrete. Although glass aggregate increased compressive strength, it provided less tensile strength for flexural behavior. Thus, this kind of aggregate is not recommended for structural applications. However, due to its insulating effects, it can be used effectively in architectural, non-load bearing panels to act as a building insulator. Additionally, the glass can add an aesthetic aspect to the structure.
- Glass pozzolan is a promising replacement for cement. The compressive strength increased by 3% compared to regular concrete when a 20% glass powder was used as cement replacement. The glass pozzolan gains strength faster with time compared to regular concrete. This is supported by literature and by the 90 days compressive test results presented in this report.

- The concrete with glass pozzolan developed the highest internal temperature compared to the other mixes.
- Although the beams with glass pozzolan developed the highest internal temperature, this did not affect the flexural capacity of the concrete. In beams with no fire exposure the load capacity is increased 10%, beams with 30 minutes heat treatment showed a load capacity increase of 22% and beams with a 1-hour heat exposure showed a load capacity increase of 100%. Using 20% glass pozzolan as cement replacement increased the flexural load capacity of concrete in beams with no heat exposure and in beams with fire damage.

Glass is a promising component for concrete mixtures. Even after fire exposure, the concrete using glass can perform adequately, and in some cases better than conventional concrete. Glass aggregate can safely be used in concrete mixtures for flatwork, or architectural components as it increases compressive strength, and has an insulating effect. This provides a quality material that can help increase the material performance while reusing material from landfills. However, its use is not recommended for use in structural members, as glass aggregate affects the tensile strength of concrete. Glass pozzolan is an effective replacement for cement. Using the recommended 20% replacement, the compressive strength and flexural strength is increased. This type of glass can be safely added to structural components. Also, as literature states, the fine particles of glass pozzolan are less likely to develop alkali-silica reaction, which is the main concern with the use of glass in concrete. This new cement replacement alternative can enhance construction materials and reduce environmental pollution by reducing the volume of glass in landfills and reducing the amount of CO_2 generated in cement production.

5.2 Recommendations for Future Work

The following are recommendations for future research involving the use of glass components in concrete.

- Study the effects of glass components in reinforcement bonding.
- Further study the compressive strength at several concrete ages to better understand the strength gain curve.
- Study grain size distribution of glass aggregates effects on concrete mixtures.
- Study the durability of concrete, analyzing the long-term effects of alkali-silica reaction, and mitigate those effects.
- Study ways to safely incorporate glass aggregate in structural components, by adding admixtures, or adding processed glass culets.
- Investigate other concrete properties such as creep, shrinkage and density when glass components are used.
- Study the effects of heat in glass concrete, analyze the internal material changes (microscopic analyzes after heat treatment).
- Analyze the behavior of glass concrete when used with materials such as CFRP.
- Use non-destructive methods to analyze glass concrete and evaluate the accuracy of those methods.

Appendix A. Concrete Mix Design

Mix Design for 1 yd^3

Use Txi Portland cement - 3500 Psi

Slump = 2 in

Size of glass aggregate = 5/8”, Max Size of natural aggregate = 1”

Non-air entrained concrete

From table 7.2 of handout – 300 lb of water / yd^3, W/C = 0.51

0.51 = 300/ Weight of cement

Weight of cement = 590 lb/yd^3

Specific gravity of cement = 3.15

Volume of cement = 590/ 3.15* 62.4 = 3.00 ft^3/yd^3

Aggregate calculation –

Fineness modulus of sand = 2.7

Coarse aggregate unit weight = 95 pcf

Specific gravity of sand= 2.65

From table 7.5 - 0.68

Volume of coarse aggregate = 0.68*27 = 17.36 ft^3/yd^3

Weight of coarse aggregate = 18.36 * 95 = 1744.2 lb/yd^3

Volume of sand using absolute volume method = 8.64 ft^3

Weight of sand = 8.64 *2.65 *62.4 = 1428.71 lb.

Volume of VCAS pozzolan (20% replacement) = 3.00 ft *0.20 = 0.6 ft^3

Weight of VCAS = .6 *2.6*62.4 = 98 lb.

Volume of glass aggregate for replacement on 6 beams.

6 beams volume = 0.30 yd^3

18.36*.30 = 5.52 ft^3

(30% glass aggregate replacement = 5.52*.3 = 1.66 ft^3, (round up to 2 ft^3)

Specific gravity of glass = 2.0-2.5, assume 2.5.

Weight of glass required = 2*2.5*62.4 = 312 lb.

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