DEVELOPMENT OF GEOPOLYMER CONCRETE FOR PRECAST STRUCTURES

by

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Abstract

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This study presents ‘geopolymer’ as a new binder to replace Portland cement in concrete to make concrete more environmentally friendly and durable. This utilizes industrial by-products like fly ash which is disposed in landfills. Therefore, the use of geopolymer as a binder in concrete production not only reduces the emission of CO_2 because of elimination of cement, but also utilizes an industrial by-product to produce a green and sustainable construction material.

In this research, the fly ash and alkaline liquid (mix of sodium hydroxide and sodium silicate) were used as the basic constituents of the geopolymer. More than 1000 cylinders were prepared using different mix designs and tested in accordance to American Standard Testing and Material (ASTM) C39 for comparing compressive strength. Geopolymer and reinforced concrete pipes were produced, tested according to ASTM C497, and compared in terms of crack pattern. In addition, factors such as molarity of sodium hydroxide, size and amount of aggregates, curing temperature, curing method and time, types of fly ash and addition of crumb rubber or steel fibers that influence the compressive strength were studied. The result showed that the mix design prepared with 9.42% CaO fly ash of 14M cured at 24hrs./158°F/oven containing amounts of larger sized aggregates produced the maximum compressive strength.

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Chapter 1

Introduction, Literature Review and Goals and Objectives

1.1 Introduction

1.1.1 General

Concrete is the most widely used building material in the world after water because of its versatile application. The essential ingredient of concrete is Portland cement (PC), which is not considered an environmentally friendly material. The key reaction involved in the manufacture of PC is the breakdown of calcium carbonate into calcium oxide and carbon dioxide (CO_2). The production of PC not only uses up a considerable amount of energy but also emits a substantial amount of CO_2 and other greenhouse gases (Mehta, 2002).

In the present context, global warming is one of the greatest environmental issues. Global warming is caused by the emission of greenhouse gases like CO_2 to the atmosphere. It has been reported that the worldwide cement industry contributes around 1.65 billion tons of the greenhouse gas emissions annually (Malhotra, 2002; McCaffrey, 2002; Hardjito et al., 2004). The production of one ton of PC emits approximately one ton of CO_2 into the atmosphere (Davidovits, 1994c; McCaffrey, 2002). Due to the production of PC, it is estimated that by the year 2020, emissions will rise by about 50% from the current levels (Naik, 2005; Salloum, 2007).

In order to reduce the environmental impact due to cement production, it is necessary to develop a new type of binder. In this respect, the geopolymer technology proposed by Davidovits (1978) is one of the revolutionary developments resulting in a low-cost and greener substitute for PC. Geopolymer concrete is an innovative binder material and is produced by totally replacing PC. It is demonstrated that geopolymeric cement generates 5-6 times less CO_2 than PC, thus helping to reduce global warming (Davidovits, 2005).

Geopolymer concrete is alkali-activated binder produced by a polymeric reaction of alkaline liquids with the silicon and the aluminum oxides in source materials of geological origin like metakaolinite (calcined kaolinite) or by-product materials such as fly ash and rice husk ash (Davidovits, 1999). Therefore, it not only helps to generate less CO_2 than PC but also reuses industrial waste and/ or by-products of alumino-silicate composition to produce added-value construction material products (Malhotra, 2002; Davidovits, 2005).

It has been reported that coal combustion production (CCP) constitutes the nation's second largest waste stream after municipal solid waste in US. About 130 MT of CCP was produced in 2011 and out of this, 56.57 MT (43.50%) was utilized (ACAA 2011 Coal Combustion Product Production & Use Survey Report). The main types of CCPs are fly ash, bottom ash, boiler slag, and flue gas desulfurization materials (FGD). Out of 130 MT of CCP, about 59.9 MT was categorized as fly ash. About 22.9 MT (38.36%) of fly ash was utilized and the rest was disposed in landfills or surface impoundments, which were lined with compacted clay soil, a plastic sheet or both. The US Environmental Protection Agency (EPA) is currently developing the beneficial applications of fly ash. This will probably reduce health issues of serious concern related to heavy metals and radioactive minerals concentration built – up over time from fly ash disposal. Utilization of fly ash as a base material in making geopolymer concrete replaces PC as well as using industrial byproducts producing a green construction material.

Beneficial use of fly ash in concrete production not only reduces greenhouse gas emissions but also the water requirement for mix design, the energy needed to produce concrete and it creates longer-lasting, more durable products that do not have to be replaced frequently. Thus, the proper utilization preserves hundreds of thousands of acres currently used for the disposal of coal combustion products, as well as protects aquifers and surface bodies of fresh water via the elimination of fly ash disposal sites while at the same time conserving natural resources for other purposes.

1.1.2 Geopolymer Mix Design for this Research

Geopolymer is being studied extensively as it shows promise as a greener substitute for PC. In the case of geopolymer, the research has been shifting from the chemistry domain to engineering application and commercial production of geopolymer concrete. Geopolymer concrete is considered to have good engineering properties (Rangan, 2008; Sumajouwn et al., 2008). This research investigates the compressive strength of geopolymer concrete.

In this research, the basic mix proportions for the majority of trial mixtures were based upon previous research on the geopolymer mix designs. Different trial mixes were produced in order to get the optimized mix design for geopolymer concrete. The basic constituents of geopolymer are low calcium fly ash and alkaline liquid. The alkaline liquid was prepared by mixing sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3) solution. The mass of the sodium hydroxide flakes in the solution depends on the concentration of the solution i.e molarity. The molarity is defined as number of moles of solute per liter of solution.

$$\text{Molarity} = \frac{\text{moles of solute}}{\text{liters of solution}} \qquad \text{——} (1)$$

Figure 1-1 Calculation of Molarity of Solution

Table 1-1 Calculation of Moles of Solute

Molarity of Solution (M)	Moles of solute (gm)	Moles of solute (lb)
1	40	0.09
8	320	0.71
12	480	1.06
14	560	1.23
17	680	1.5

The silicon and aluminum oxides in the fly ash react with the alkaline liquid to form the geopolymer paste that binds the loose coarse and fine aggregates, and other un-reacted materials together to form the geopolymer concrete.

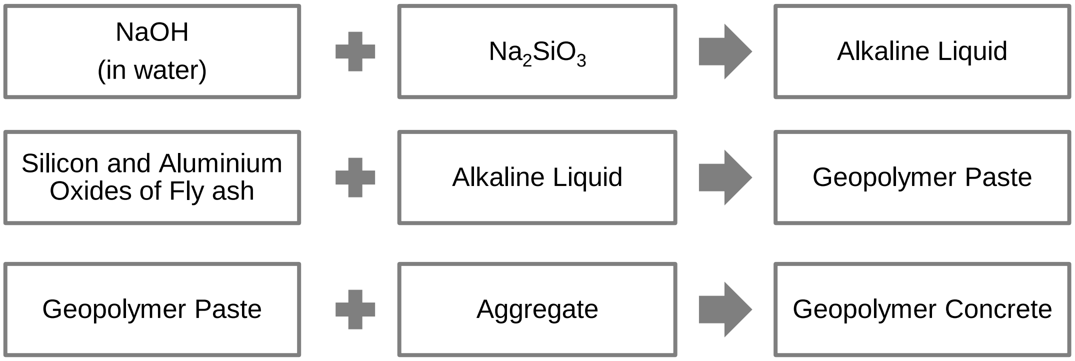


Figure 1-2 Preparation of Geopolymer Concrete

There are different factors which influence the compressive strength of the geopolymer concrete. In this research, some of the important factors were studied:

1. Molarity of sodium hydroxide solution (8M, 12M, 14M, 17M)
2. Sizes and amounts of aggregates (3/8 or 5/8 or both)
3. Curing Temperature (Room temperature, 75°F, 95°F, 115°F, 131°F, 158°F, 170°F)
4. Curing method (Room or Oven or Steam)
5. Curing time (24 hours or 48 hours)

6. Types of fly ash – varies with the percentage of CaO (14.14%, 9.42%, 1.29%)
7. Extra Additive – Steel Fibers or Crumb Rubber (by replacing 7.5% by volume of sand or 15% by volume of sand)

In order to study the effect of each factor, only one factor was varied and all the other factors were held constant. For example, in order to study the effect of concentration of sodium hydroxide in terms of Molarity in the compressive strength (8M, 12M, 14M), the variable parameter was the molarity and all the other constituents and curing conditions like types of fly ash, amount of aggregates and chemicals, curing time, curing temperature and method were held constant.

1.2 Literature Review

1.2.1 Geopolymer

1.2.1.1 General

The term ‘geopolymer’ was first coined by French scientist Joseph Davidovits (1978) to represent a broad range of materials characterized by networks of inorganic molecules. Geopolymer is an alumino-silicate polymer synthesized from predominantly silicon (Si) and aluminum (Al) materials of geological origin like metakaolinite or industrial by-products such as fly ash or slag. The polymerization process involves a fast chemical reaction under a highly alkaline condition of Si-Al minerals resulting in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds in amorphous form (Davidovits, 1994).

Poly(sialate) is the term used for the chemical designation of geopolymer based on silico-aluminate (Davidovits, 1988a, 1988b, 1991; Van Jaarsveld et al., 2002a); Sialate is an abbreviation for silicon-oxo-aluminate. Poly(sialates) are chain and ring polymers with Si^{4+} and Al^{3+} in IV-fold coordination with oxygen and range from amorphous to semi-crystalline with the empirical formula:

$$M_n(-(-SiO_2)_z\ -AlO_2)_n.H_2O \qquad \text{——} (4)$$

Figure 1-3 Empirical Formula of Poly(sialate)

where “z” is 1,2 or 3 or higher up to 32; M is a monovalent cation such as potassium or sodium, and “n” is a degree of polycondensation (Davidovits, 1988b, 1991, 1994b, 1999). The structures of these polysialates can be schematized as in Figure 1-4.

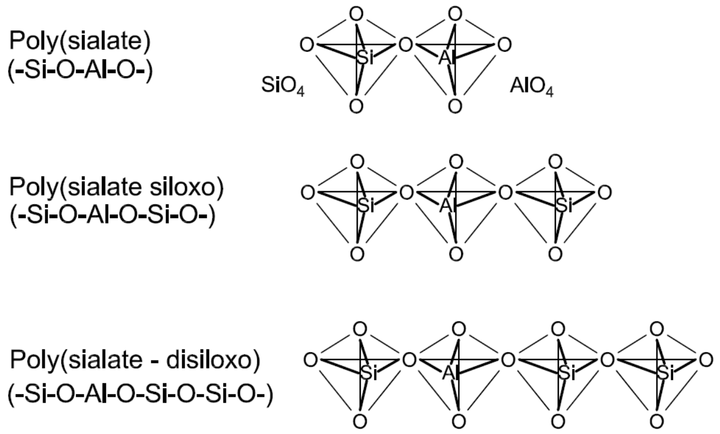
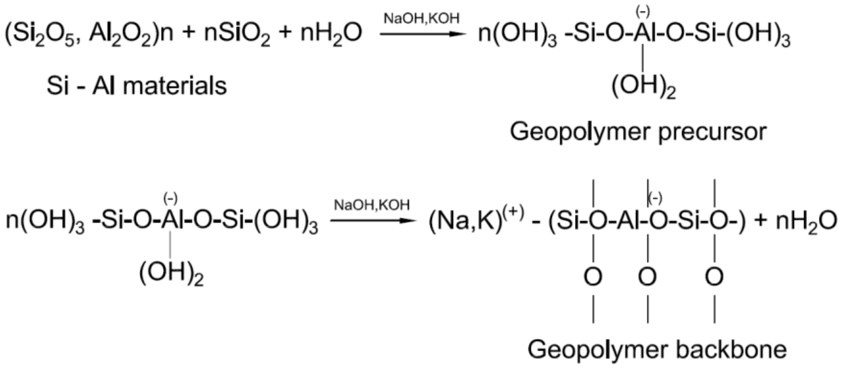


Figure 1-4 Chemical Structures of Polysialates (Davidovits, 1988b; 1991; 1994b; 1999)

The schematic formation of geopolymer material by polycondensation can be shown as described by Equations (5) and (6):



$$\underset{\text{Si - Al materials}}{(Si_2O_5, Al_2O_2)n + nSiO_2 + nH_2O} \xrightarrow{NaOH,KOH} \underset{\text{Geopolymer precursor}}{n(OH)_3\text{-Si-O-}\overset{(-)}{\underset{\underset{(OH)_2}{|}}{Al}}\text{-O-Si-}(OH)_3} \quad \text{—— (5)}$$

$$n(OH)_3\text{-Si-O-}\overset{(-)}{\underset{\underset{(OH)_2}{|}}{Al}}\text{-O-Si-}(OH)_3 \xrightarrow{NaOH,KOH} \underset{\text{Geopolymer backbone}}{(Na,K)^{(+)} - (\text{Si-}\overset{|}{\underset{\underset{\underset{|}{O}}{|}}{O}}\text{-Al-}\overset{|(-)}{\underset{\underset{\underset{|}{O}}{|}}{O}}\text{-Si-}\overset{|}{\underset{\underset{\underset{|}{O}}{|}}{O}}\text{-})} + nH_2O \quad \text{—— (6)}$$

Figure 1-5 Schematic Formation of Geopolymer Material (Davidovits, 1994; Van Jaarsveld et al., 1997)

The second equation shows that water is released during the chemical reaction that results in the formation of geopolymers. This water is expelled from the geopolymer matrix during the curing and further drying periods leaving behind discontinuous nano-pores in the matrix which provides benefits to the performance of geopolymers. Therefore, the water in a geopolymer mix plays no role in the chemical reaction but increases the workability of the mixture during handling. This is in contrast to the chemical reaction of water in a Portland cement concrete mixture during the hydration process.

Unlike PC, geopolymers do not form calcium silicate-hydrates (CSHs) for matrix formation and strength, but utilize the polycondensation of silica and alumina precursors and a high alkali content to attain structural strength. Therefore, geopolymers are sometimes referred to as alkali-activated alumino silicate binders (Davidovits, 1994a; Palomo et al., 1999; Roy, 1999; Van Jaarsveld et al., 2002a). This binder is the main reaction product of ‘Alkali-activation of fly ash’ (AAFA). AAFA is a physical-chemical process in which the powdery solid i.e. fly ash is mixed with a concentrated alkali solution in a suitable proportion to produce a workable and moldable paste (Bakri et al., 2011). However, Davidovits (1999, 2005) stated that using the term ‘alkali-activated’ could create significant confusion and generate false ideas about geopolymer concrete. For example, the use of the term ‘alkali-activated cement’ or ‘alkali-activated fly ash (AAFA)’ can be confused with the term ‘Alkali-aggregate reaction (AAR)’, a harmful property well known in concrete. In Alkali-aggregate reaction (AAR), some aggregates react with the alkali hydroxides in concrete, causing expansion and cracking over a period of many years.

1.2.1.2 Constituents of Geopolymer

The main constituents of geopolymer are the source materials and the alkaline liquids. The geopolymer is used together with aggregates to produce geopolymer concrete. Extra additives like crumb rubber and steel fibers can also be added to the geopolymer concrete mix.

1.2.1.2.1 Source materials: The source materials for geopolymers should be rich in Silica and Aluminia. Natural minerals like kaolinite, clays, micas, andalousite, spinel etc or by-product materials like fly ash, slag, rich-husk ash, silica fume, red mud etc can be used as the source materials. The choice of the source materials for making geopolymer depends on factors such as availability, cost, and type of application and specific demand of the user.

Depending on the nature of the source material, it is stated that the calcined source materials, such as fly ash, slag, calcined kaolin, demonstrated a higher final compressive strength when compared to those made using non-calcined materials, for example kaolin clay, mine tailings and naturally occurring minerals (Barbosa et al. 2000). However, Xu and van Deventer (2002) found that using a combination of calcined (e.g. fly ash) and non-calcined material resulted in significant improvement in compressive strength and reduction in reaction time.

Among the by-product materials, fly ash and slag are proven to have the potential source materials for making geopolymers. Fly ash is produced during the combustion of coal in coal-fired power plants. It is considered to be advantageous due to its high reactivity that comes from its finer particle size than slag.

The chemical composition of fly ash can vary considerably, but all fly ash includes: Silicon dioxide (SiO_2), Calcium oxide (CaO), Iron (III) oxide (Fe_2O_3) and Aluminium oxide (Al_2O_3). Depending on the calcium oxide content in the fly ash, it can be classified into two types: Type “C” and Type “F”.

Type C fly ash is produced from the burning of younger lignite or subbituminous coal. It contains more than 20% CaO and generally higher alkali and sulfate contents. It has pozzolanic and also some self-cementing properties. In the presence of water, it will harden and gain strength over time. It does not require an activator for self-cementing purpose.

Low-calcium fly ash is produced from the burning of harder, older anthracite and bituminous coal. This is pozzolanic in nature and contains less than 20% CaO. The addition of alkaline liquid (mix of sodium or potassium hydroxide and sodium or potassium silicate) leads to the formation of geopolymer.

Van Jaarsveld et. al. (2003) reported that the particle size, calcium content, alkali metal content, amorphous content, and morphology and origin of the fly ash affected the properties of geopolymers. It was revealed that the calcium content in fly ash played an important role in strength development and final compressive strength as the higher calcium content resulted in faster strength development and higher compressive strength. However, Fernandez-Jimenez & Palmo, (2003) claimed that in order to obtain the optimal binding properties of the material, fly ash as a source material should have low calcium content and other characteristics such as unburned material lower than 5%, Fe_2O_3 content not higher than 10%, 40-50% of reactive silica content, 80-90% particles with size lower than 45 µm and high content of vitreous phase. Gourley (2003) also stated that the presence of calcium in fly ash in significant quantities could interfere with the polymerization setting rate and alters the microstructure. Therefore, it seems that the use of Low-calcium (ASTM Class F) fly ash is more preferred as a source material than High-calcium (ASTM Class C) fly ash to make geopolymer (Wallah and Rangan, 2006).

1.2.1.2.2 Alkaline liquids: The alkaline liquids are from soluble alkali metals usually based on sodium (Na) or potassium (K). Sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3) mixed with sodium hydroxide (NaOH) or potassium hydroxide (KOH) is the most common type of alkaline liquid used in the geopolymerization (Davidovits, 1999; Palomo et al., 1999; Barbosa et al., 2000; Xu and van Deventer, 2000; Swanepoel and Strydom, 2002; Xu and van Deventer, 2002).

Palomo et al (1999) concluded that the type of alkaline liquid played an important role in the polymerization process. Reactions occurred at a high rate when the alkaline liquid contained soluble silicate, either sodium or potassium silicate, compared to the use of only alkaline hydroxides. They used the combination of sodium hydroxide with sodium silicate or potassium hydroxide with potassium silicate as alkaline liquids. Xu and van Deventer (2000) confirmed that the addition of sodium silicate solution to the sodium hydroxide solution as the alkaline liquid enhanced the reaction between the source material and the solution. Furthermore, after a study of the geopolymerization of sixteen natural Al-Si minerals, they found that generally the NaOH solution caused a higher extent of dissolution of minerals than the KOH solution.

1.2.1.2.3 Crumb rubber and steel fibers: Crumb rubber (Figure 1-6) is a term used to define recycled rubber from automotive and truck scrap tires. During the recycling process, steel and fluff is removed leaving tire rubber with a granular consistency. Continued processing with a granulator and/or cracker mill, possibly with the aid of cryogenics or mechanical means, reduces the size of the particles further. Crumb rubber is sized by the mesh screen or sieve through which it passes in the production process (TNRCC information).

Dramix® 3D steel fibers (Figure 1-7), produced by Bekaert Company, are used as reinforcement in this research. These fibers have durable quality with smooth and corrosion-free surfaces. This provides easy mixing and fast switching.

Crumb rubber or steel fibers were added to the geopolymer concrete mix for the comparison of compressive strength of plain and reinforced geopolymer concrete.

Figure 1-6 Crumb Rubber

Figure 1-7 Steel Fibers

1.2.2 Pipe Manufacturing Method

There are two methods of manufacturing pipes:

1. Wet Cast
2. Dry Cast.

Wet cast uses a concrete mix that is wet relative to the mixes used in other processes. In this case, the water-cement ratio is 0.4 or higher and usually contains a slump less than 4 inch. This method is used for the production of large diameter pipes.

Dry cast uses a concrete mix with a zero slump and has a water-cement ratio of 0.3 to 0.36. As soon as the concrete consolidates, the form can be stripped off. Thus the producer only needs a few sets of forms for mass production. This is typically used for mass production of products like concrete pipes or manholes and also in concrete block production.

In this research, geopolymer concrete pipes were produced by the dry cast method using a Packerhead Machine (Figure 1-8). In this method, concrete is deposited onto the conveyor, which is delivered to the forms set under the discharge end of the conveyor. Metal pipe forms or three-piece jackets, creating the outer diameter of the pipe, are placed by a forklift onto the openings in a circular casting floor. The roller head (Figure 1-9) is sent inside the mold. As concrete is poured, the roller head rotates at high speed while moving up and down. The inside diameter of the pipe is created by the spinning of the rollers which force the concrete to the outer edges against the jacket by radial compaction. A forklift moves the cast pipe to a curing area where the exterior form is immediately removed.

Figure 1-8 Packerhead Machine

Figure 1-9 Roller Heads of Packerhead Machine

1.3 Goals and Objectives

The general goals of this study are to compare the compressive strength of cylinders prepared from different types of low calcium based geopolymer mix designs, and to study the parameters that affect the compressive strength of the geopolymer concrete.

The main objectives of the study are:

1. To prepare the mix design with the maximum compressive strength.
2. To determine the factors which influence the compressive strength of the geopolymer concrete.
3. To study the difference in crack patterns between geopolymer concrete pipe and reinforced concrete pipe.

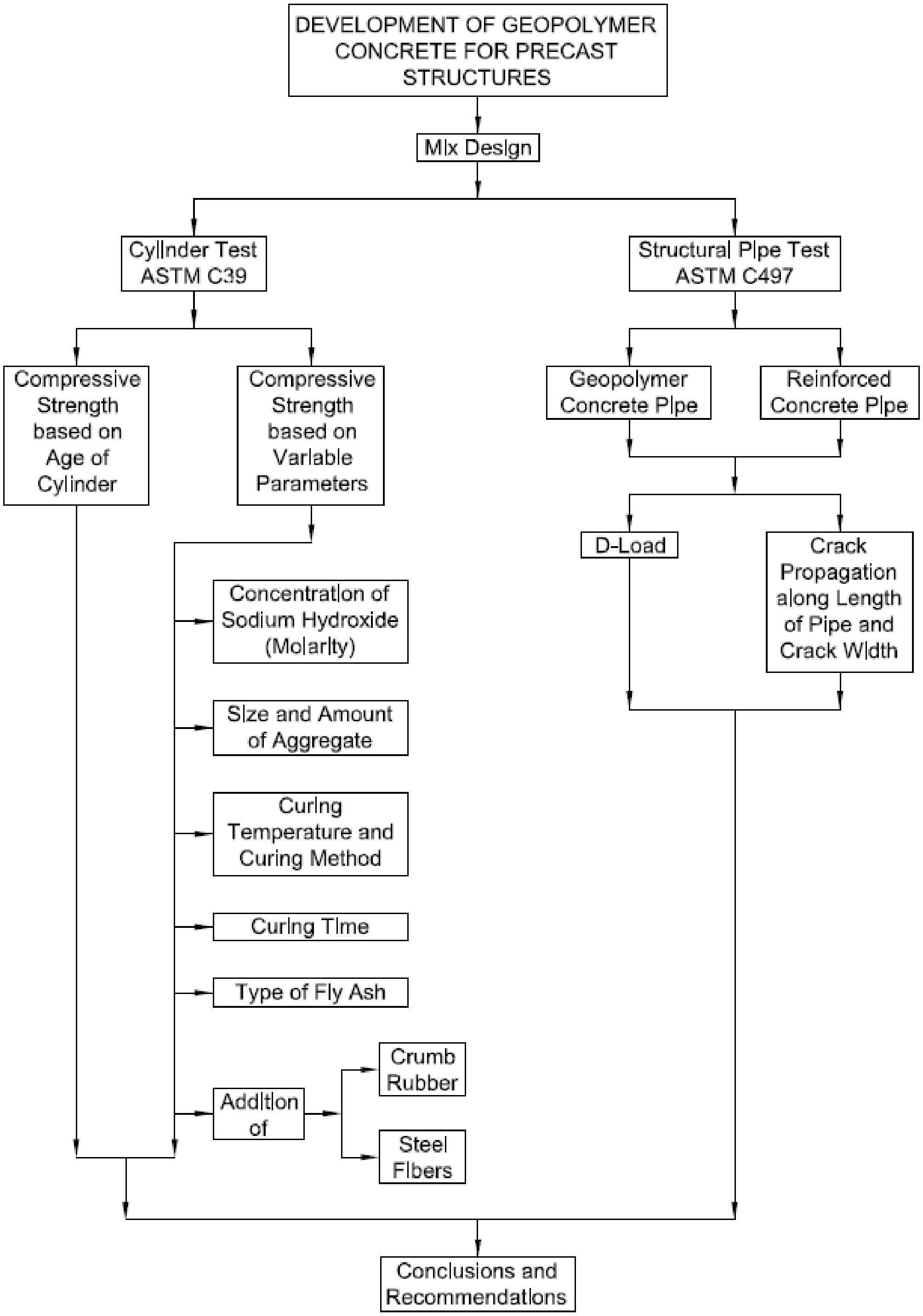


Figure 1-10 Outline of the Research

Chapter 2

Material Development and Testing

2.1 Introduction

This chapter describes the experimental work performed in the laboratory. It presents the different types of mix designs produced and the material behavior results of testing the geopolymer concrete cylinders under compression according to ASTM C39 ‘Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens’.

The materials used for making geopolymer concrete specimens in this research are low-calcium dry fly ash as the source material, aggregates of different sizes, alkaline liquid, water and super plasticizer.

The fly ashes used in this study were supplied from two different ash marketers, Boral Material Technology and Headwaters resources. Boral Material Technology supplied the fly ash from Stillesboro, GA and Rockdale, TX while Headwaters resources supplied it from Jewett, TX. The fly ash from Stillesboro, GA contained 1.29% CaO and that from Rockdale, TX 9.42% CaO. The fly ash from Jewett, TX was found to have 14.14% CaO. The ASTM C618 ‘Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete’ Test Reports of the fly ash are presented in Appendix A.

A combination of sodium hydroxide solution and sodium silicate solution was used as the alkaline liquid. Sodium hydroxide in the form of flakes was purchased from a local supplier. Sodium silicate solution (Na_2O=10.6%, SiO_2=26.5% and density=1.39g/ml at 25^0C) was also purchased from a local supplier.

More than 1000 cylinders were produced during the research using different mix designs and were tested in accordance with ASTM C39.

2.2 Geopolymer Mix Design

The basic procedure for preparing the typical geopolymer mix was consistent. The required amount of sodium hydroxide flakes, depending on the concentration of sodium hydroxide solution i.e. molarity, was weighed and dissolved in 1 liter of water. The hydroxide solution was left for about an hour to allow the exothermically heated liquid to cool to room temperature. The required amount of hydroxide solution was weighed and added to the measured sodium silicate solution. The alkaline solution was prepared 24 hours prior to use.

On the next day, super plasticizer (SP) and an extra amount of water, if needed, was added to the solution. Different types of aggregate (3/8, 5/8 and sand) were first mixed in the concrete mixer and fly ash was added to it and rotated for about 4 minutes. The solution was shaken properly, poured in the mixer and rotated for about 4-5 minutes. In this way, the geopolymer concrete mix was prepared.

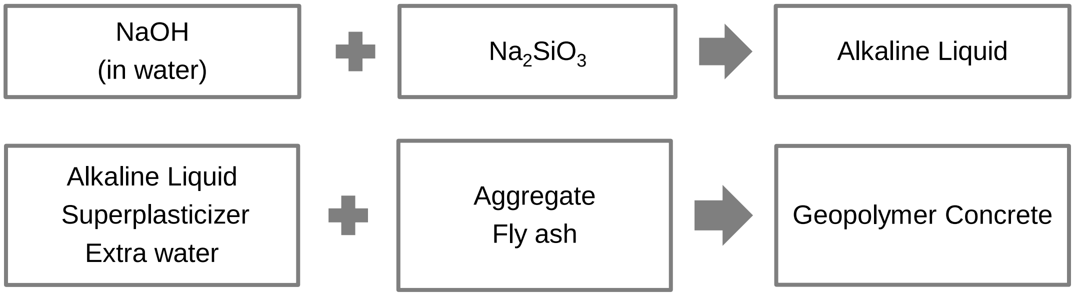


Figure 2-1 Procedure of preparing Geopolymer Concrete

In order to prepare the geopolymer concrete mix with the crumb rubber, the volume occupied by a certain amount of sand was replaced by the same volume of crumb rubber. The required amount of sand was weighed in a container and the volume occupied by the sand was marked. The same volume of crumb rubber was taken and mixed with the alkaline liquid prepared 24 hours prior to use. After an hour, SP and water were added to this solution. Aggregates were first mixed and fly ash was added to it. Finally, the solution with the crumb rubber was added to the mix.

To prepare the geopolymer concrete mix with the steel fibers, the required amount of steel fibers were weighed and mixed to the solution prepared 24 hours prior to use. After an hour, the steel fibers were separated and mixed with aggregates in the mixer. Fly ash was added to the mix and the solution with SP and water was shaken and poured in the mixer.

In this way, the different mix designs were produced for research purposes.

Figure 2-2 Constituents of Geopolymer

Figure 2-3 Geopolymer Mix with 5/8 aggregates

Figure 2-4 Geopolymer Mix without 5/8 aggregates

Figure 2-5 Preparing of Geopolymer Concrete in Concrete Mixer

Table 2-1 shows the design mixes with different percentage of CaO in fly ash and with curing environment.

Table 2-1 Details of Mixtures 1 through 8

Mix #	*Fly Ash (lb/ft^3)*	*Aggregate (lb/ft^3)*			*Sodium Hydroxide Solution (lb/ft^3)*	*Sodium Silicate Solution (lb/ft^3)*	*Concentration of Sodium Hydroxide Solution (M)*	*SP (lb/ft^3)*	*Added Water (lb/ft^3)*	*Curing*		
		3/8	*5/8*	*Sand*						*Time (hrs.)*	*Temp. (°F)*	*Method*
1	25.5(a)	50	15	50	2.6	6.5	14	0.4	1	24	115	Steam
2	25.5(a)	50	15	50	2.6	6.5	14	0.4	1	24	131	Oven
3	25.5(a)	50	15	50	2.6	6.5	14	0.4	1	24	158	Oven
4	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	24	115	Oven
5	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	24	131	Oven
6	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	24	158	Oven
7	25.5(c)	80	-	35	2.6	6.5	14	0.4	-	24	158	Oven
8	25.5(c)	80	-	35	2.6	6.5	8	0.4	-	24	158	Oven

Note: (a) Fly Ash: 14.14% CaO (b) Fly Ash: 9.42% CaO (c) Fly Ash: 1.29% CaO

2.3 Geopolymer Material Tests

2.3.1 Compressive Cylinder Test

2.3.1.1 Introduction

Cylinders were produced from different mix designs and tested according to ASTM C39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.” In this test, the compressive load was applied axially to the cylinder at a rate within a prescribed range until failure occurred. The compressive strength of the cylinder was then determined by dividing the maximum load obtained during the test by the cross-sectional area of the cylinder. Cylinders of 4 inch x 8 inch (100 mm x 203 mm) diameter were produced and tested at 1, 3, 7, and in some cases, 28 days after production. Since the cylinders were prepared by using dry cast method, the compressive strength obtained on 7 days was sufficient for comparison purpose.

The cylinders were produced and tested in the Civil Engineering Laboratory Building (CELB) at the University of Texas at Arlington. The cylinder specimens were produced using plastic molds to assure the correct dimensions. Mold release agent was applied to the interior of the molds to ease the removal of the casted specimen. The molds were securely placed onto a vibrating table near the batching location. Concrete mix was placed in multiple lifts, compacted and tamped while under vibration. At least eight cylinders were prepared from each mix design. After curing, the cylinders were stripped from their molds and capped at each end so as to create a smooth and leveled testing surface (ASTM C617). Sulfur flake was used as a capping material.

2.3.1.2 Test Set up

The testing equipment had compressive capabilities up to 500kips. The machine was power operated and applied load continuously at the prescribed loading rate as described below. It consisted of two steel bearing blocks with hardened faces, one of which remained on the upper surface of the cylinder and the other on which the cylinder rested. The bearing faces of the blocks should be at least 3% greater in diameter than the testing specimen. The cylinder was placed in the machine and centered relative to the upper bearing block. Before starting the test, the machine was adjusted until the cylinder and the upper block came in contact. The typical test set up is given in Figure 2-6.

Figure 2-6 500 Kips Compressive Cylinder Testing Machine

Figure 2-7 Loading Apparatus

2.3.1.3 Loading History

The rate at which the cylinder was tested was 35 ± 7 psi/s (0.25 ± 0.05 Mpa/s). This was applied continuously and slowly without shock, throughout the test. ASTM C39 states that higher loading rates can be applied during the first half of the loading phase but should be in a controlled manner so that the cylinder is not subjected to shock loading. As it reached the ultimate load, there was no need to adjust the rate of movement and the stress rate decreased due to cracking in the cylinder. The compressive load was applied until the load indicator showed that the load decreased steadily. The loading rate was applied manually and was displayed in the digital reader. Figure 2-7 shows the part of the testing apparatus which controlled the rate.

2.3.1.4 Test Results

After completion of all cylinder tests, data were accumulated and compressive strengths were compared. Table 2-2 gives the compressive strength with respect to age of cylinder.

Table 2-2 Compressive Strength of Mixtures 1 through 8

Mix #	*Compressive Strength (ksi)*				*Remarks*
	1 Day	*3 Days*	*7 Days*	*28 Days*	
1	3.39	4.48	5.44	-	
2	3.75	4.34	4.73	-	
3	1.81	2.08	2.42	-	
4	3.4	4.48	4.74	5.46	
5	3.75	4.35	5.44	5.68	
6	5.68	6.7	7.13	7.23	Maximum Strength
7	1.2	1.34	1.5	-	
8	4.45	4.83	4.83	-	

In the case of 14.14% CaO fly ash, the maximum strength at 7 days was 5.44 ksi (37.51 Mpa) obtained from the cylinder cured at 115°F in steam with a NaOH concentration of 14M (Figure 2-8). Only crack lines appeared on the surface of the cylinder and the cylinder was less brittle compared to the cylinders prepared from the other two types of fly ash (Figure 2-9). For 9.42% CaO fly ash, the maximum strength at 7 days was 7.13 ksi (49.16 Mpa) found from the cylinder cured at 158°F in an oven with a

NaOH concentration of 14M (Figure 2-10). The cylinder was brittle and cracked into pieces (Figure 2-11). In case of 1.29% CaO fly ash, the maximum compressive strength at 7 days was 4.83 ksi (33.3 Mpa) obtained from the cylinder cured at 158°F in an oven with a NaOH concentration of 8M (Figure 2-12). The cylinder cracked in an inclined pattern (Figure 2-13).

Among these eight mixes prepared by using three different types of fly ash, the mix design with 9.42% CaO fly ash was found to have the maximum strength. The maximum strength at 28 days was found to be 7.23 ksi (49.85 Mpa). These data also show a gradual increase in compressive strength with respect to age of cylinder.

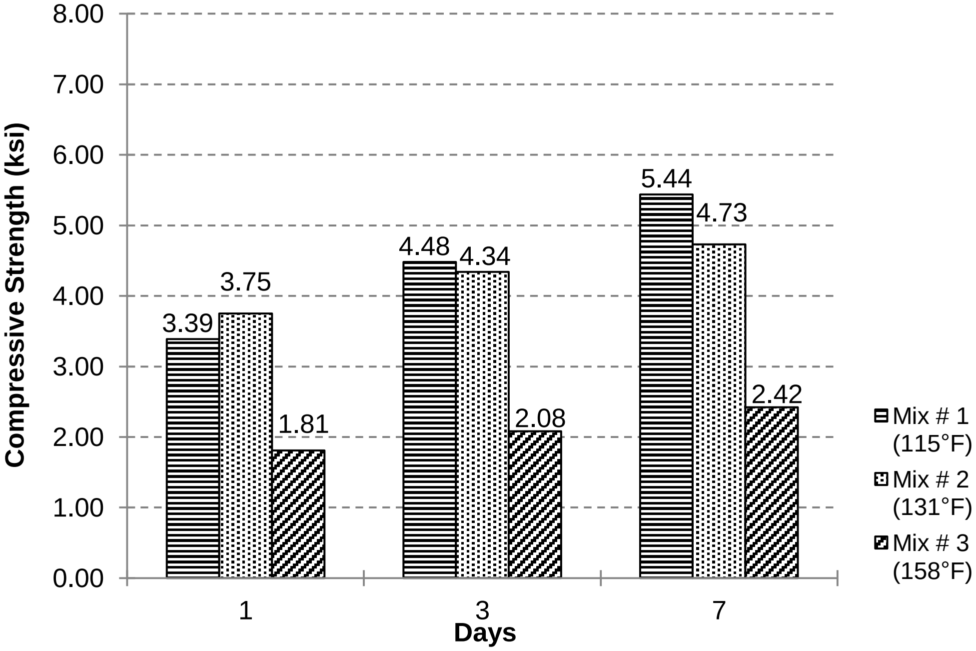


Figure 2-8 Compressive Strength of Mix of 14.14% CaO Fly Ash (1, 2 and 3)

Figure 2-9 Failure pattern of Cylinder of 14.14% CaO Fly Ash

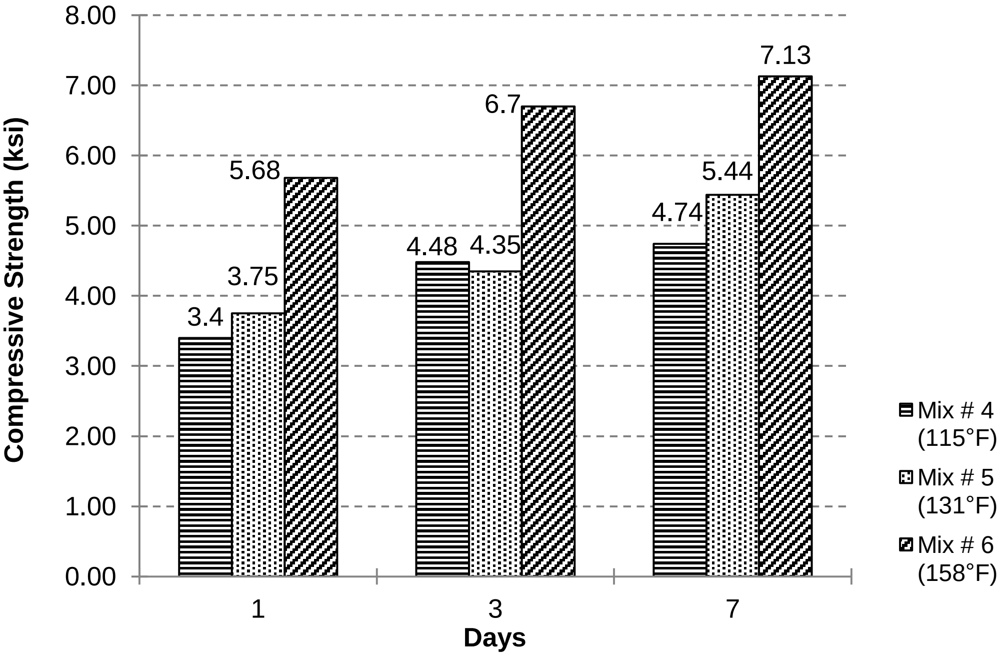


Figure 2-10 Compressive Strength of Mix of 9.42% CaO Fly Ash (4, 5 and 6)

Figure 2-11 Failure pattern of Cylinder of 9.42% CaO Fly Ash

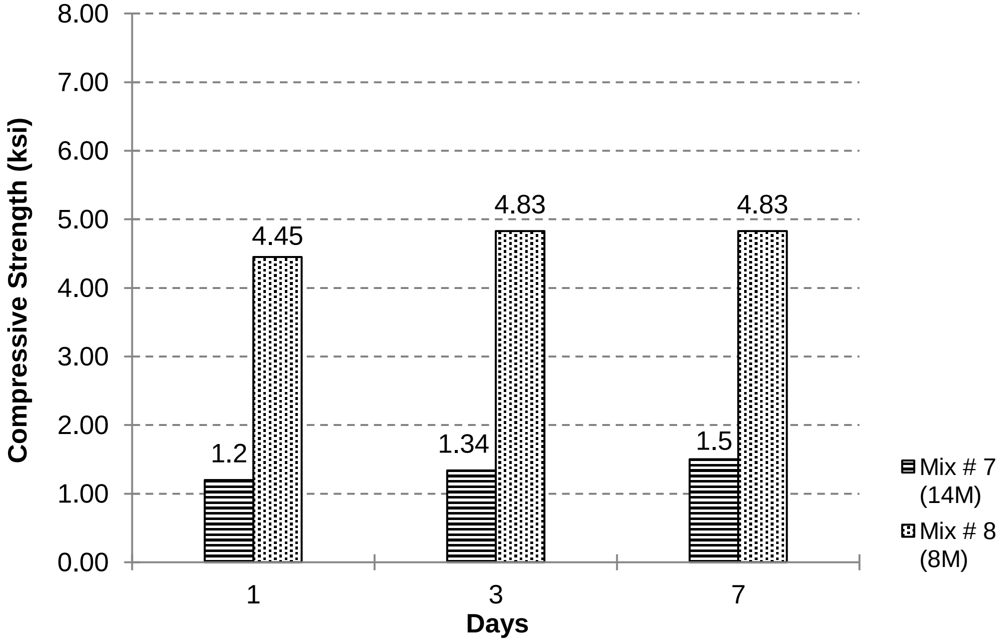


Figure 2-12 Compressive Strength of Mix of 1.29% CaO Fly Ash (7 and 8)

Figure 2-13 Failure pattern of Cylinder of 1.29% CaO Fly Ash

Despite the same mix design, it is possible to obtain different results due to different factors.

1. It is difficult to measure the exact amount of the constituents of the mix.
2. In order to avoid the formation of dry mix (Figure 2-14), it is necessary to maintain the amount of water and properly mix the constituents of the concrete.
3. It is not possible to cast the dry mix.
4. Inadequate compaction significantly results in the formation of voids (Figure 2-16) and lowers ultimate performance of the concrete.
5. Placement of the fresh concrete requires skilled operatives to ensure adequate compaction to attain the full strength and durability of the hardened concrete.
6. It is necessary to cap the surfaces of cylinder to form smooth and leveled surfaces (Figure 2-15) and to distribute the stress equally (Figure 2-17).

Figure 2-14 Dry Mix

Figure 2-15 Inclined capping

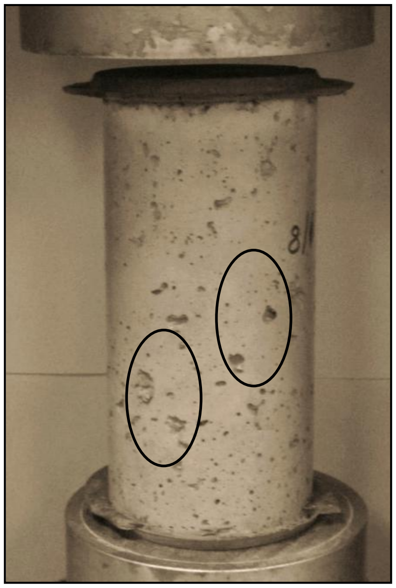


Figure 2-16 Presence of voids

Figure 2-17 Stress Distribution on left side

2.3.2 Effect of Variable Parameters

There are different parameters which affect the compressive strength of geopolymer concrete. In order to study the effects of these parameters, the mean value of the compressive strength of at least two concrete cylinders tested on the same day was considered. The parameters studied are as follows:

1. Molarity of sodium hydroxide solution (8M, 12M, 14M)
2. Sizes and amounts of aggregates (3/8 or 5/8 or both)
3. Curing temperatures (115°F, 131°F, 158°F) and Curing methods (Oven or Steam)
4. Curing time (24 hours or 48 hours)
5. Types of fly ash – varies with the percentage of CaO (14.14%, 9.42%, 1.29%)
6. Addition of Crumb Rubber (by replacing 7.5% by volume of sand)
7. Addition of Steel fibers

While studying the effect of variable parameters, only one parameter was varied and all the rest of the parameters were held constant. For example, in order to study the effect of size and amount of aggregates in the compressive strength, the variable parameter was the size and amount of aggregates (3/8 or 5/8 or both) and all the rest of the constituents and curing conditions like concentration of sodium hydroxide, types of fly ash, amount of chemicals, curing time, curing temperature and method were considered constant. The compressive strength at 7 days was considered for comparison purposes.

Table 2-3 Mix Design 1 through 4 with Compressive Strength (Molarity of sodium hydroxide solution)

Mix #	*Fly Ash (lb/ft^3)*	*Aggregate (lb/ft^3)*			*Sodium Hydroxide Solution (lb/ft^3)*	*Sodium Silicate Solution (lb/ft^3)*	*Conc. Of NaOH (M)*	*SP (lb/ft^3)*	*Added Water (lb/ft^3)*	*Curing*			*Compressive Strength (ksi) at 7 Days*
		3/8	*5/8*	*Sand*						*Time (hrs.)*	*Temp. (°F)*	*Method*	
1	$25.5^{(b)}$	80	-	35	2.6	6.5	12	0.4	1	24	158	Oven	4.9
2	$25.5^{(b)}$	80	-	35	2.6	6.5	14	0.4	1	24	158	Oven	5.65
3	$25.5^{(c)}$	80	-	35	2.6	6.5	8	0.4	-	24	158	Oven	4.83
4	$25.5^{(c)}$	80	-	35	2.6	6.5	14	0.4	-	24	158	Oven	1.5

Table 2-4 Mix Design 5 through 10 with Compressive Strength (Sizes and amounts of aggregates)

Mix #	*Fly Ash (lb/ft^3)*	*Sodium Hydroxide Solution (lb/ft^3)*	*Sodium Silicate Solution (lb/ft^3)*	*Conc. Of NaOH (M)*	*SP (lb/ft^3)*	*Added Water (lb/ft^3)*	*Curing*			*Aggregate (lb/ft^3)*			*Compressive Strength (ksi) at 7 Days*
							Time (hrs.)	*Temp. (°F)*	*Method*	*3/8*	*5/8*	*Sand*	
5	$25.5^{(a)}$	2.6	6.5	14	0.4	1	24	131	Oven	50	15	50	4.73
6	$25.5^{(a)}$	2.6	6.5	14	0.4	1	24	131	Oven	80	-	35	4.06
7	$25.5^{(a)}$	2.6	6.5	14	0.4	1	24	131	Oven	60	-	55	3.86
8	$25.5^{(b)}$	2.6	6.5	14	0.4	1	24	131	Oven	50	15	50	5.44
9	$25.5^{(b)}$	2.6	6.5	14	0.4	1	24	131	Oven	80	-	35	4.06
10	$25.5^{(b)}$	2.6	6.5	14	0.4	1	24	131	Oven	60	-	55	3.86

Note: $^{(a)}$ Fly Ash: 14.14% CaO $^{(b)}$ Fly Ash: 9.42% CaO $^{(c)}$ Fly Ash: 1.29% CaO

Table 2-5 Mix Design 11 through 18 with Compressive Strength (Curing temperatures and Curing methods)

Mix #	*Fly Ash (lb/ft^3)*	*Aggregate (lb/ft^3)*			*Sodium Hydroxide Solution (lb/ft^3)*	*Sodium Silicate Solution (lb/ft^3)*	*Conc. Of NaOH (M)*	*SP (lb/ft^3)*	*Added Water (lb/ft^3)*	*Curing*			*Compressive Strength (ksi) at 7 Days*
		3/8	*5/8*	*Sand*						*Time (hrs.)*	*Temp. (°F)*	*Method*	
11	25.5(a)	50	15	50	2.6	6.5	14	0.4	1	24	115	Steam	5.44
12	25.5(a)	50	15	50	2.6	6.5	14	0.4	1	24	131	Oven	4.73
13	25.5(a)	50	15	50	2.6	6.5	14	0.4	1	24	158	Oven	2.42
14	25.5(b)	50	15	50	2.6	6.5	12	0.4	1	24	115	Oven	2.41
15	25.5(b)	50	15	50	2.6	6.5	12	0.4	1	24	131	Oven	2.58
16	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	24	115	Oven	4.74
17	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	24	131	Oven	5.44
18	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	24	158	Oven	7.13

Table 2-6 Mix Design 19 through 22 with Compressive Strength (Curing time)

Mix #	*Fly Ash (lb/ft^3)*	*Aggregate (lb/ft^3)*			*Sodium Hydroxide Solution (lb/ft^3)*	*Sodium Silicate Solution (lb/ft^3)*	*Conc. Of NaOH (M)*	*SP (lb/ft^3)*	*Added Water (lb/ft^3)*	*Curing*			*Compressive Strength (ksi) at 7 Days*
		3/8	*5/8*	*Sand*						*Temp. (°F)*	*Method*	*Time (hrs.)*	
19	25.5(b)	50	15	50	2.6	6.5	12	0.4	1	131	Oven	24	2.58
20	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	131	Oven	24	5.44
21	25.5(b)	50	15	50	2.6	6.5	12	0.4	1	131	Oven	48	4.93
22	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	131	Oven	48	5.60

Note: (a) Fly Ash: 14.14% CaO (b) Fly Ash: 9.42% CaO (c) Fly Ash: 1.29% CaO

Table 2-7 Mix Design 23 through 25 with Compressive Strength (Types of fly ash)

Mix #	Fly Ash (lb/ft^3)	Aggregate (lb/ft^3)			Sodium Hydroxide Solution (lb/ft^3)	Sodium Silicate Solution (lb/ft^3)	Conc. Of NaOH (M)	SP (lb/ft^3)	Added Water (lb/ft^3)	Curing			Compressive Strength (ksi) at 7 Days
		3/8	5/8	Sand						Time (hrs.)	Temp. (°F)	Method	
23	25.5(a)	80	-	35	2.6	6.5	14	0.4	1	24	158	Oven	2.85
24	25.5(b)	80	-	35	2.6	6.5	14	0.4	1	24	158	Oven	5.65
25	25.5(c)	80	-	35	2.6	6.5	14	0.4	-	24	158	Oven	1.5

Table 2-8 Mix Design 26 through 27 with Compressive Strength (Addition of Crumb rubber)

Mix #	Fly Ash (lb/ft^3)	NaOH Sol^n (lb/ft^3)	Na_2SiO_3 Sol^n (lb/ft^3)	Conc. Of NaOH (M)	SP (lb/ft^3)	Added Water (lb/ft^3)	Curing			Aggregate (lb/ft^3)			Crumb Rubber (% by vol. of sand)	Comp. Strength (ksi) at 7 Days
							Time (hrs.)	Temp. (°F)	Method	3/8	5/8	Sand		
26	25.5(b)	2.6	6.5	14	0.4	1	24	75	Steam	80	-	35 - 2.6 = 32.4	7.5% of 35 = 2.6	1.6
27	25.5(b)	2.6	6.5	14	0.4	1	24	75	Steam	80	-	35	-	1.64

Table 2-9 Mix Design 28 through 29 with Compressive Strength (Addition of Steel fibers)

Mix #	Fly Ash (lb/ft^3)	Aggregate (lb/ft^3)			NaOH Sol^n (lb/ft^3)	Na_2SiO_3 Sol^n (lb/ft^3)	Conc. Of NaOH (M)	SP (lb/ft^3)	Added Water (lb/ft^3)	Curing			Steel Fiber (lb/ft^3)	Comp. Strength (ksi) at 7 Days
		3/8	5/8	Sand						Time (hrs.)	Temp. (°F)	Method		
28	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	24	115	Steam	1.48	3.1
29	25.5(b)	50	15	50	2.6	6.5	14	0.4	1	24	115	Steam	-	5.44

Note: (a) Fly Ash: 14.14% CaO (b) Fly Ash: 9.42% CaO (c) Fly Ash: 1.29% CaO

2.3.2.1 Molarity of Solution

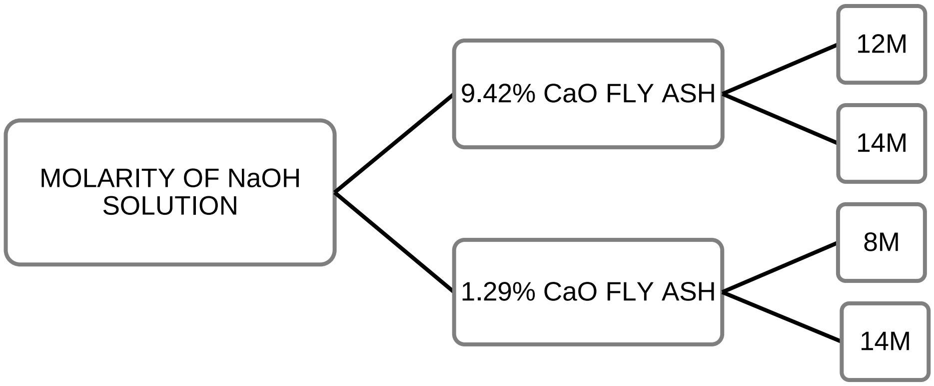


Figure 2-18 Molarity of Solution

Mixes 1 through 4 (Table 2-3) were made to study the effect of concentration of sodium hydroxide (NaOH) solution in terms of molarity on the compressive strength of the concrete. In Table 2-3, the different concentration (M) of NaOH solution are given in the 6th column. Two types of fly ash, 9.42% CaO fly ash and 1.29% CaO fly ash were considered for this purpose.

Figure 2-19 shows that in terms of the 9.42% CaO fly ash, mix 2 with a higher concentration of NaOH solution (14M) yielded a higher compressive strength at 7 days than mix 1 with the lower concentration of NaOH solution (12M). While in the case of 1.29% CaO fly ash, mix 3 with a lower concentration of NaOH solution (8M) yielded a higher compressive strength than mix 4 with the higher concentration of NaOH solution (14M). This indicates that the compressive strength of the geopolymer concrete varies with the molarity of the NaOH solution depending on the types of fly ash.

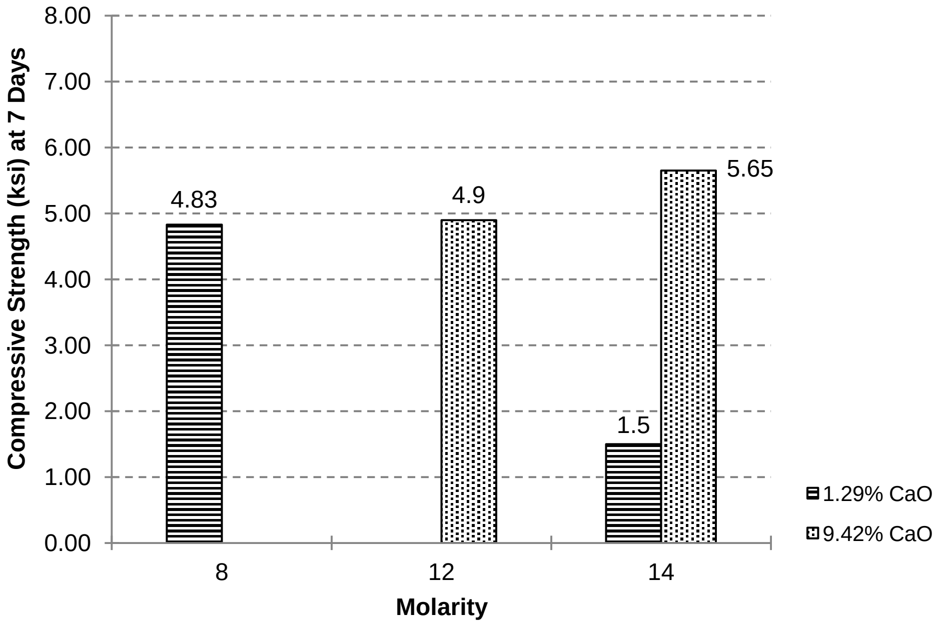


Figure 2-19 Effect of Molarity on Compressive Strength of Geopolymer Concrete (Mix 1 through 4)

2.3.2.2 Size and Amount of Aggregates (3/8 or 5/8 or both)

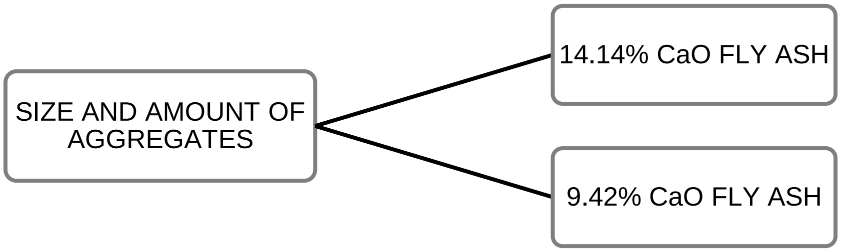


Figure 2-20 Size and Amount of Aggregates

Mixes 5 through 10 (Table 2-4) were prepared to study the effect of size and amount of aggregates on the compressive strength of the concrete. Three types of mixes, A, B and C with different sizes and amounts of aggregates were prepared (Table 2-10). In Table 2-4, the different sizes and amounts of aggregates are given in the 9th column.

Figure 2-21 shows that the presence of more amounts of larger size aggregates increased the compressive strength of the geopolymer concrete. The use of well graded and different sized aggregates with rough surfaces provides better interlocking between them and thus helps to improve the compressive strength.

Table 2-10 Types of Mix

Type of Mix	*Aggregate (lb/ft^3)*		
	3/8	*5/8*	*Sand*
A	50	15	50
B	80	-	35
C	60	-	55

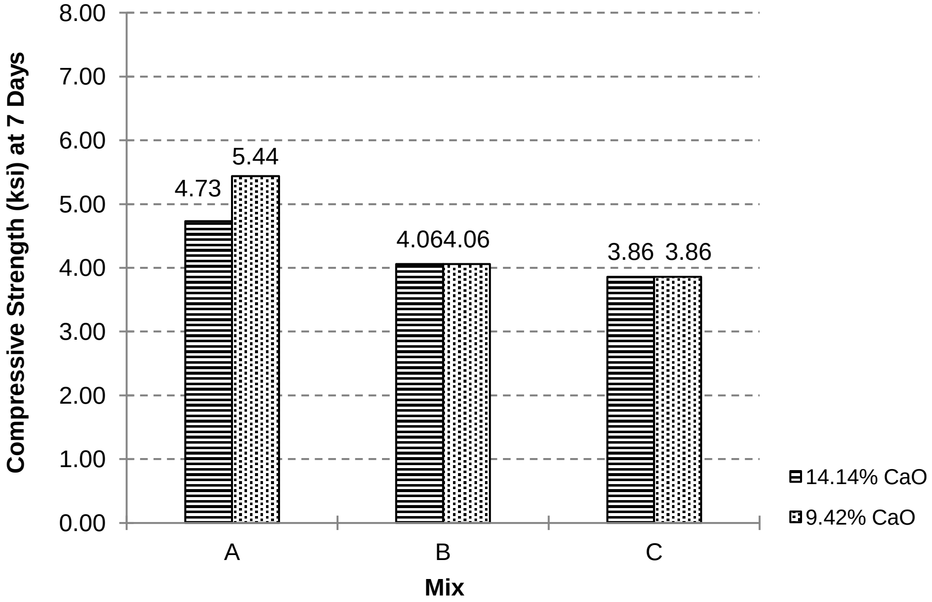


Figure 2-21 Effect of use of different sizes and amounts of aggregates on Compressive Strength of Geopolymer Concrete (Mix 5 through 10)

2.3.2.3 Curing Temperature and Curing Method

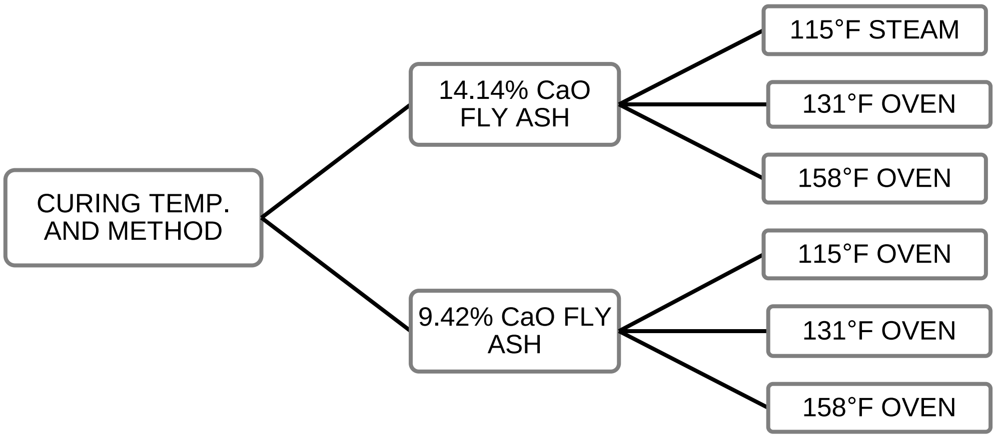


Figure 2-22 Curing Temperature and Curing Method

Mixes 11 through 18 (Table 2-5) were made to study the effect of different curing temperatures and curing methods on the compressive strength of the concrete. The curing methods include oven – curing (Figure 2-23) or steam - curing (Figure 2-24). In Table 2-5, the different types of curing temperatures and curing methods used are given in the 9th column.

Figure 2-25 shows that the highest compressive strength for 14.14% CaO fly ash was obtained by curing in steam at 115°F and the compressive strength decreased with an increase in temperature. But for 9.42% CaO fly ash, Figure 2-26 shows that compressive strength increased with the increase in temperature and the highest compressive strength was obtained by curing at 158°F in an oven.

It can be concluded that curing temperatures and methods influence the compressive strength of the geopolymer concrete depending on the types of fly ash.

Figure 2-23 Oven Curing

Figure 2-24 Steam Curing

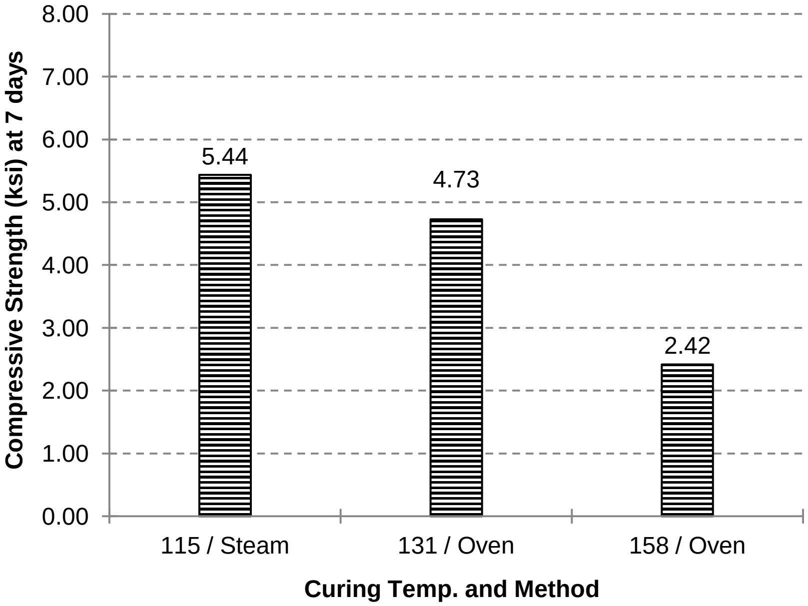


Figure 2-25 Effect of Curing Temperatures and Methods on Compressive Strength of Geopolymer Concrete with 14.14% CaO Fly Ash (Mix 11 through 13)

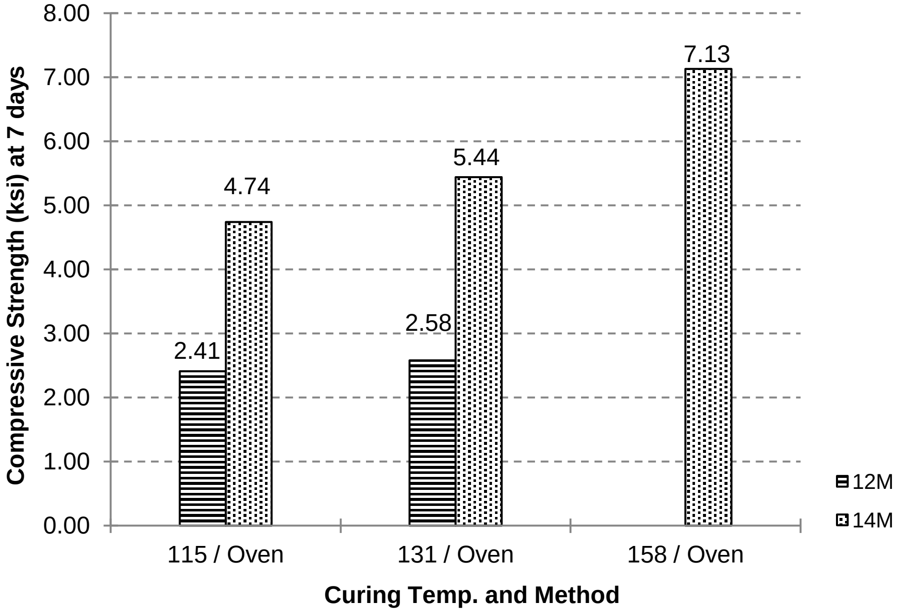


Figure 2-26 Effect of Curing Temperatures and Methods on Compressive Strength of Geopolymer Concrete with 9.42% CaO Fly Ash (Mix 14 through 18)

2.3.2.4 Curing Time

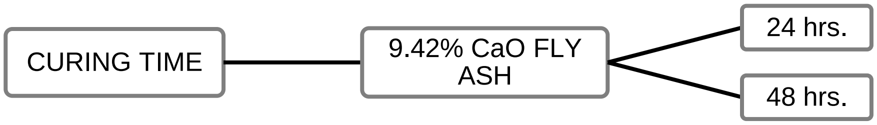


Figure 2-27 Curing Time

Mixes 19 through 22 (Table 2-6) were prepared to study the effect of curing time on the compressive strength of the concrete. The mixes were cured for 24 and 48 hours. In Table 2-6, the different curing times are given in the 9^{th} column.

Figure 2-28 shows that the mix cured for 48 hours yielded more compressive strength than the mix cured for 24 hours. This indicates that the compressive strength increases with an increase in curing time of the geopolymer concrete.

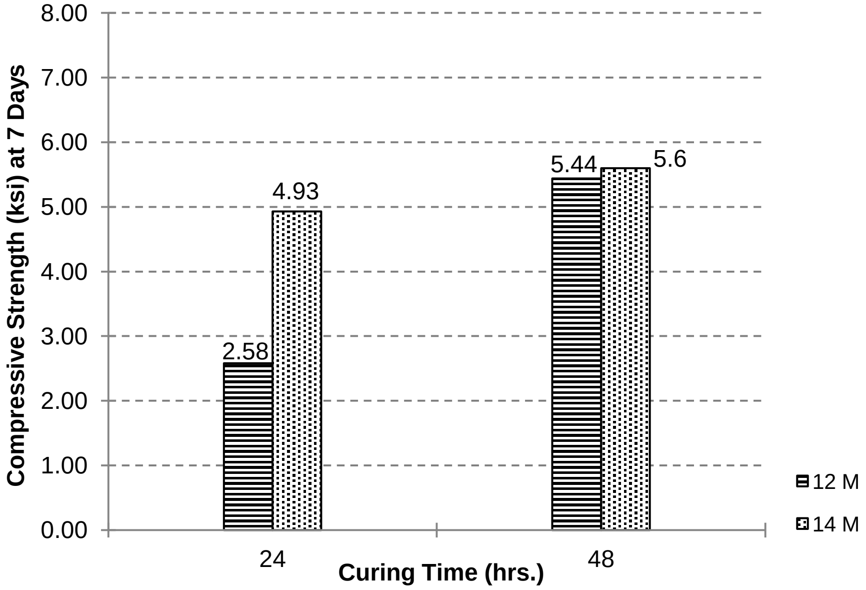


Figure 2-28 Effect of Curing Times on Compressive Strength of Geopolymer Concrete (Mix 19 through 22)

2.3.2.5 Types of Fly Ash

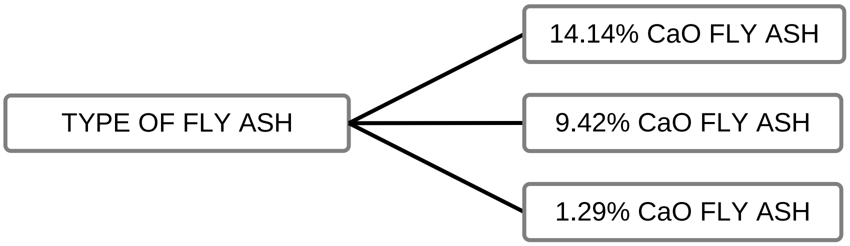


Figure 2-29 Types of Fly Ash

Mixes 23 through 25 (Table 2-7) were made to study the effect of percentage of CaO in the fly ash on the compressive strength of the concrete. In Table 2-7, the different types of fly ash are given in the 2nd column. The chemical composition of fly ash varies with its place of origin (Appendix A).

Figure 2-30 shows that mix 23 containing the fly ash of 9.42% CaO had the highest 7 days compressive strength of 5.65 ksi. It can be concluded that the percentage of CaO present in the fly ash plays a significant role in the compressive strength of the geopolymer concrete.

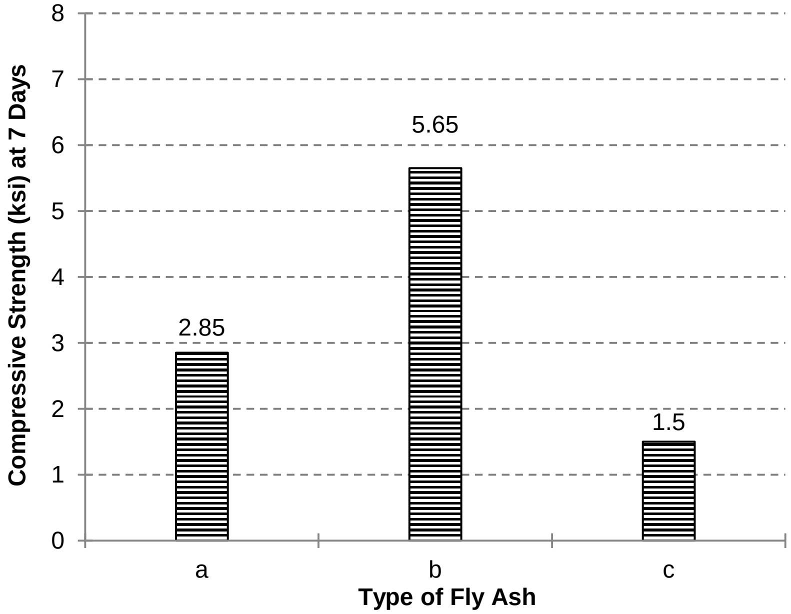


Figure 2-30 Effect of different types of Fly Ash on Compressive Strength of Geopolymer Concrete (Mix 23 –25)

Note:

(a) Fly Ash:	14.14% CaO
(b) Fly Ash:	9.42% CaO
(c) Fly Ash:	1.29% CaO

2.3.2.6 Addition of Crumb Rubber (by replacing 7.5% by vol. of sand)

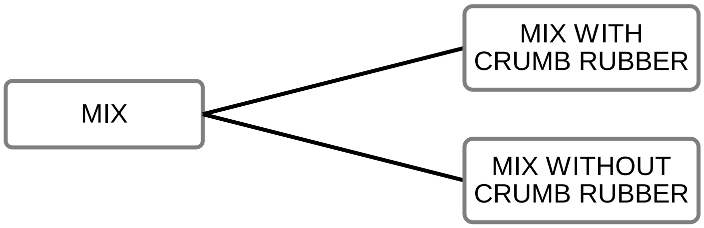


Figure 2-31 Types of Mix

Mix 26 (Table 2-8) was prepared to study the effect on the concrete compressive strength resulting from the addition of crumb rubber. In the case of mix 26, a certain volume of fine aggregate (sand) i.e. 7.5% was replaced by crumb rubber.

Figure 2-32 shows that there is a slight decrease in compressive strength with the addition of crumb rubber, however, the failure pattern of the cylinder prepared from plain geopolymer concrete was different compared to the geopolymer concrete cylinder with crumb rubber (Figure 2-33).

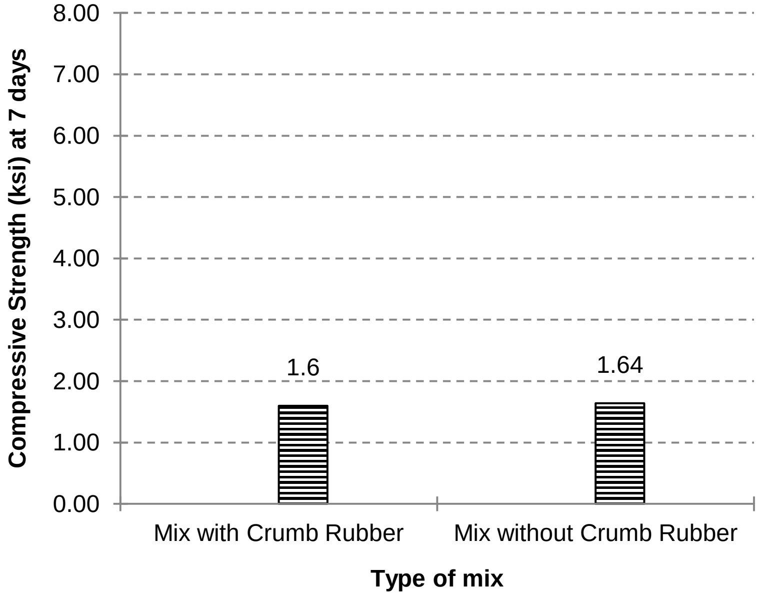


Figure 2-32 Effect of Mix with and without crumb rubber on Compressive Strength of Geopolymer Concrete (Mix 26 and 27)

a) Plain geopolymer concrete cylinder

b) Geopolymer concrete cylinder with Crumb rubber

Figure 2-33 Failure patterns of cylinders (a) and (b)

2.3.2.7 Addition of Steel Fibers

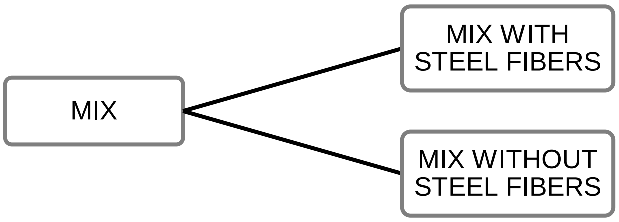


Figure 2-34 Types of Mix

Mix 28 (Table 2-9) was made to study the effect on the compressive strength of concrete resulting from the addition of steel fibers. To prepare the mix, 40 lb/yd^3 (1.48 lb/ft^3 or 23.73 kg/m^3) steel fibers was added to the geopolymer mix. It was very difficult to prepare a good workable mix with the steel fibers. Different mixes were produced but they tended to be so dry that they could not be casted. The workability and compressive strength of the mix cannot be predicted, even when using the same mix design.

Figure 2-35 shows that the addition of steel fibers does not improve the compressive strength. It was found that the steel fibers do not bond completely with the concrete along the entire length of the fiber.

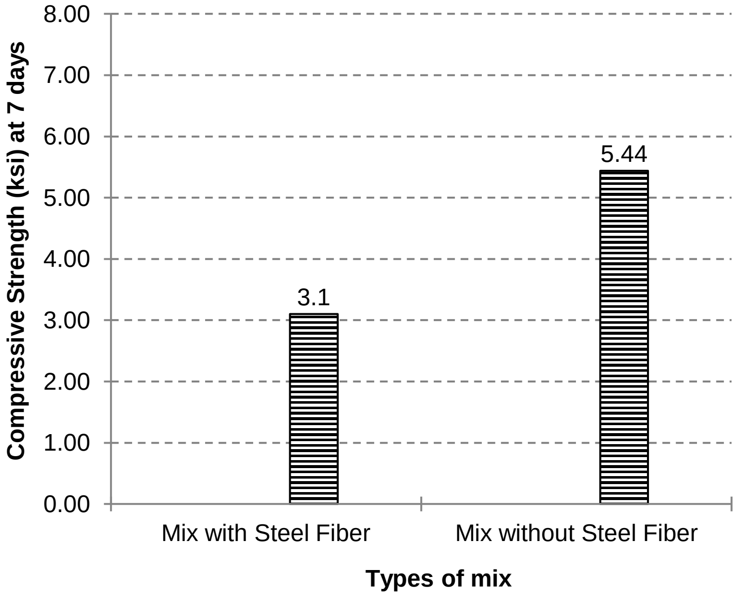


Figure 2-35 Effect of Mix with and without Steel Fiber on Compressive Strength of Geopolymer Concrete (Mix 28 – 29)

The advantage of using the steel fibers was that the cylinders with steel fibers were less brittle than the cylinders without steel fibers (Figure 2-36). The use of steel fibers also prevented the additional tensile failure cracks. The failure patterns of cylinders with steel fibers (Figure 2-37) were different with respect to the age of cylinder. When performing 3 days test, the cylinders were found to be brittle and showed inclined cracks but less brittle than the cylinders made from plain geopolymer. When the cylinders were tested on the 14 days, they showed few vertical hairline cracks.

c) Plain geopolymer concrete cylinder

d) Geopolymer concrete cylinder with Steel Fibers

Figure 2-36 Failure patterns of cylinders (c) and (d)

3 Days

7 Days

14 Days

Figure 2-37 Failure patterns of cylinder with steel fibers

Chapter 3

Structural Testing

3.1 Introduction

This chapter describes the method of testing of the structural strength of the concrete pipe in accordance with ASTM C497 “Standard Test Methods for Concrete Pipe, Manhole Sections, or Tile”.

The geopolymer concrete pipe and reinforced concrete pipe of 24 inch (610mm) diameter and 4 feet (1219mm) length were produced at Hanson Pipe and Precast located at Grand Prairie, TX. The pipes were tested on the 7 days of production according to three-edge bearing, method explained in ASTM C497, for determining the structural strength of the concrete pipes under the application of the external force. The pipe designation used for the reinforced concrete pipe is name of production plant – diameter of pipe – thickness type – pipe type. For example, HAN-24-B-RCP represents Reinforced concrete pipe of Hanson Plant with 24 inch diameter and B wall thickness.

The following mix design (Table 3-1) was used for preparing the geopolymer concrete pipe.

Table 3-1 Detail of Mix design

Constituents		lb/ft^3
Aggregates	5/8	0
	3/8	80
	Sand	35
Fly Ash (Rock Dale-9.42%)		25.5
Sodium Silicate Solution		6.5
Sodium Hydroxide solution (12M)		2.6
Super plasticizer		0.4
Added water		1
Curing (Time/ Temp./ Method)		24hrs./ Room temp.

While performing three-edge bearing test, the surface of the pipe should be dry. The testing was done in a machine capable of exerting a crushing force in a vertical plane extending along the full length of the pipe. The machine should be rigid so that the distribution of the test load is uniform along the length of the pipe without any deformation or yielding of any parts of the machine.

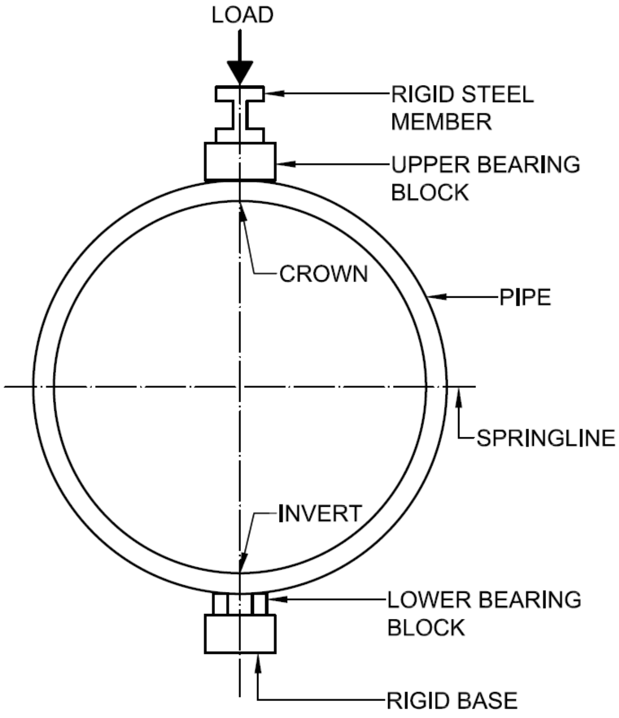


Figure 3-1 Three-Edge Bearing Test

The pipe was supported on a lower bearing and the load was applied through an upper bearing (Figure 3-1). The lower bearing block consisted of two wood or hard rubber strips fastened to a wooden or steel beam or direct to a concrete base so as to prevent substantial deflection under the application of maximum load. The deflection should be less than $^{1}/_{720}$ of the length of the pipe. The wood or rubber strips should be rectangular in cross section of not less than 2 inch in width and less than 1 inch or more than 1½ inch in height and should have the top inside corners rounded to a radius of ½ inch. In the case of rubber strips, it should have a durometer hardness of not less than 45 or more than 60.

The upper bearing should be a hard wood beam with or without an attached hard rubber strip fastened to a steel or wood-faced steel beam. The dimension of the beam should be such that the deflection is less than $^{1}/_{720}$ of the length of the pipe under the application of maximum load. If the hard rubber strip was used, it should follow the same requirement as explained for the lower bearing.

3.2 Test Set up

The testing machine should be capable of providing constant rate of load required for pipe of specific diameter. The two supports at the bottom of the machine were adjusted for the specific pipe diameter but the interior vertical sides of the support should be parallel and spaced at a distance not more than 1 in./ft of the pipe diameter and not less than 1 inch. The bearing faces of both the upper and lower support should not vary from a straight line vertically or horizontally by more than $^{1}/_{32}$ in./ft of length under no load.

The pipe was rolled and placed on two lower bearing strips in such a way that the pipe rested firmly and was aligned to the machine. The two ends of the pipe were marked at a point midway between the lower bearing strips and the diametrically opposite point was established on each end. The upper bearing was placed aligned with these marks.

A typical setup of the pipe used for the three-edge bearing test is shown in Figure 3-2.

Figure 3-2 Test Setup

3.3 Testing Procedure

The testing machine was moved till the pipe and the top bearing of the machine came in contact without transferring any load to pipe. As per the ASTM C497, the load should be applied at a constant rate up to the maximum of 7500 lbf/linear foot of pipe from the top bearing.

3.4 Test Results

The D-load is defined as the supporting strength of the pipe loaded under the three-edge bearing test expressed in terms of pounds per linear foot per foot of inside diameter or horizontal span. This load is either 0.01-inch crack D-load or the ultimate D-load. The 0.01-inch crack D-load is the maximum load carried by a concrete pipe before having a crack of width of 0.01-inch. The 0.01-inch crack width is measured at close intervals throughout a continuous length of 1 feet or more measured parallel to the longitudinal axis of pipe barrel. The ultimate D-load is the maximum load supported by the pipe.

In this research, the three-edge bearing test was used to measure ultimate D-load. In addition, crack propagation along length of the pipe as well as crack width was also observed. As given in Table 3-2, ultimate D-load for the reinforced concrete pipe was found to be slightly more than that of the geopolymer concrete pipe.

Table 3-2 Test Result

Type of Pipe	*Dimension of Pipe*	*Reinforcement*	*Ultimate D-Load obtained (lb/ft/ft)*
Geopolymer Concrete Pipe	24" Diameter 4' Length	Use of Steel Cage	2133.5
Reinforced Concrete Pipe			2250

Figure 3-3 and 3-4 show the difference in crack pattern of geopolymer and reinforced concrete pipe. In geopolymer concrete pipe, crack lines were uniformly distributed along the length of the pipe while in reinforced concrete pipe, distinct crack line was visible. The width of the cracks in geopolymer concrete pipe was comparatively smaller than in reinforced concrete pipe. Figure 3-5 shows severe failure on the top and bottom of the reinforced concrete pipes than geopolymer concrete pipe.

(a)

(b)

Figure 3-3 Longitudinal View of Pipe (a) Geopolymer Concrete Pipe (b) Reinforced Concrete Pipe

(a)

(b)

Figure 3-4 Longitudinal View of Pipe (a) Geopolymer Concrete Pipe
(b) Reinforced Concrete Pipe

(a) (b)

Figure 3-5 Failure in Top and Bottom of Pipe (a) Geopolymer Concrete Pipe (b) Reinforced Concrete Pipe

Chapter 4

Summary, Conclusions and Recommendations

4.1 Summary

This research is aimed at investigating the effects of different types of geopolymer mix designs in the compressive strength. It also includes the study of different variable parameters that influence the compressive strength of the geopolymer concrete like molarity of sodium hydroxide solution, sizes and amounts of aggregates, curing temperatures and curing methods, curing time, types of fly ash and addition of crumb rubber or steel fibers.

In order to study the effect of variable parameters, only one parameter was varied and all the other parameters were held constant. For example, in order to study the effect of curing time in the compressive strength, the variable parameter was the curing time (24 hours, 48 hours) and all the other constituents of the mix such as concentration of sodium hydroxide, types of fly ash, amount of aggregates and chemicals, curing temperature and method were kept constant. The compressive strength at 7 days was considered for the comparison purpose.

While preparing mix with crumb rubber, the crumb rubber replaced 7.5% or 15% by volume of the sand and to prepare the mix with steel fibers, 40 lb/yd^3 (1.48 lb/ft^3) was added to the geopolymer mix.

During this research, more than 1000 cylinders, 4 inch diameter and 8 inch height, were prepared and tested according to ASTM C39 at 1, 3, 7 and in some cases, 28 days. In addition, the geopolymer concrete pipe, 24 inch diameter and 4 feet length, was produced and tested in accordance with ASTM C497 at 7 days. The geopolymer concrete pipe and the reinforced concrete pipe were compared in terms of D-load and failure pattern.

4.2 Conclusions

Throughout the research, geopolymer has been used as an alternative binder to replace Portland cement in concrete. Use of geopolymer significantly reduces emission of CO_2 and energy required to produce Portland cement. Geopolymer concrete utilizes low calcium based fly ash, which is an industrial byproduct and hazardous material to be disposed as a landfill.

Based on the test results, the following conclusions are drawn:

1. The compressive strength of the geopolymer concrete is highly influenced by the amount of CaO in the fly ash (Table 2-1, 2-2).
2. The compressive strength of the geopolymer concrete increases with the age of cylinder (Table 2-2).
3. The concentration of sodium hydroxide solution in terms of the molarity increases or decreases the compressive strength of geopolymer concrete depending on the types of fly ash (Table 2-3, Figure 2-17). Higher the concentration of sodium hydroxide higher is the compressive strength for 9.42% CaO fly ash. The maximum compressive strength was obtained from the cylinder prepared with 14M concentration of sodium hydroxide. In case of 1.29% CaO fly ash, higher the concentration of sodium hydroxide lower is the compressive strength. The maximum compressive strength was obtained from the cylinder prepared with 8M concentration of sodium hydroxide.
4. The compressive strength increases with use of amounts of larger sized aggregates (Table 2-4, Figure 2-18).
5. Different curing temperatures and curing methods were considered in order to study the compressive strength of geopolymer concrete. Depending on types of fly ash, the curing temperature and curing method increases or decreases the

compressive strength (Table 2-5). Lower curing temperature and steam curing increases the compressive strength of 14.14% CaO fly ash (Figure 2-21). The maximum compressive strength was obtained from the cylinder cured at 115°F in steam. The cylinder cured at 131°F in oven also worked well. In the case of 9.42% CaO fly ash, higher curing temperature and oven curing increases the compressive strength (Figure 2-22). The maximum compressive strength was obtained from the cylinder cured at 158°F in oven. The cylinder cured at 131°F and 115°F in oven also gave good compressive strength.

6. The curing time increases the compressive strength of the geopolymer concrete (Table 2-6, Figure 2-23).
7. The geopolymer concrete with 9.42% CaO fly ash yielded a higher compressive strength than 14.14% CaO fly ash and 1.29% CaO fly ash (Table 2-7, Figure 2-24).
8. There is a slight decrease in compressive strength with the addition of crumb rubber (Table 2-8 and Figure 2-25).
9. The addition of steel fibers in the geopolymer concrete decreased the compressive strength (Table 2-9 and Figure 2-27).
10. The highest compressive strength was found to be 7.23 ksi (49.85 Mpa). This was obtained at 28 days from 9.42% CaO fly ash containing aggregates (3/8, 5/8, sand) with 14 M concentration of sodium hydroxide cured at 24 hrs / 158°F / Oven.
11. Geopolymer concrete pipe showed hairline and less severe cracks than in reinforced concrete pipe when tested according to ASTM C497 (Figure 3-3, 3-4, 3-5).

4.3 Recommendations

This study recommends the following future research:

1. In this research, the alkaline liquid used in the geopolymerization is the combination of sodium hydroxide and sodium silicate. Hydroxide solutions greatly influence the compressive strength of the geopolymer concrete. Therefore, there is a need to research the effect of other hydroxide solutions like barium hydroxide, lithium hydroxide, and magnesium hydroxide in the compressive strength.
2. It has been observed that fly ash from different sources may vary the compressive strength of the geopolymer concrete. Thus, the effect of fly ash from different sources in the compressive strength needs to be further explored.
3. Sufficient research has not been performed related to the use of crumb rubber, steel and synthetic fibers. It is recommended to further investigate the use of crumb rubber, steel and synthetic fibers in different types of specimens.
4. Only one geopolymer pipe of 24 inch diameter with a steel cage was produced and tested according to ASTM C497. It is necessary to conduct experiments on geopolymer pipe of different diameter. Further research has to be performed using linear variable displacement transducer (LVDT) secured within the interior of the geopolymer pipe to obtain load deformation plot.

Appendix A

Composition of Fly Ash used in the Research

(ASTM C 618 TEST REPORT)

Table A-1 Composition of Class “F” Fly Ash (14.14%)

			ASTM C-618-08 SPECIFICATIONS		TXDOT DMS-4610 SPECIFICATION	
CHEMICAL ANALYSIS						
			CLASS C	CLASS F	CLASS C	CLASS F
Silicon Dioxide (SiO_2)		50.67%				
Aluminium Oxide (Al_2O_3)		18.96%				
Iron Oxide (Fe_2O_3)		6.35%				
Sum of SiO_2, Al_2O_3 and Fe_2O_3		75.98%	50 Min.	70 Min.	50 Min.	70 Min.
Magnesium Oxide (MgO)		3.12%				
Sulfur Trioxide (SO_3)		0.74%	5.0 Max.	5.0 Max.	5.0 Max.	5.0 Max.
Available Alkalis as Na_2O		0.69%				
Calcium Oxide (CaO)		14.14%				
PHYSICAL ANALYSIS						
Moisture Content		0.04%	3.0 Max.	3.0 Max.	3.0 Max.	3.0 Max.
Loss on Ignition		0.17%	6.0 Max.	6.0 Max.	3.0 Max.	3.0 Max.
Fineness: Amount retained on 325 sieve %		16.81%	34% Max.	34% Max.	34% Max.	34% Max.
Water Requirement, % Control		94%	105% Max.	105% Max.	105% Max.	105% Max.
Specific Gravity		2.46				
Autoclave Expansion, %		-0.04%	0.8% Max.	0.8% Max.	0.8% Max.	0.8% Max.
Strength Activity Index With Portland cement	7 Days	86%	75% Min.	75% Min.	75% Min.	75% Min.
	28 Days	98%	75% Min.	75% Min.	75% Min.	75% Min.

Table A-2 Composition of Class “F” Fly Ash (9.42%)

			ASTM C-618-08 SPECIFICATIONS		AASHTO M 295 SPECIFICATION	
CHEMICAL ANALYSIS						
			CLASS C	CLASS F	CLASS C	CLASS F
Silicon Dioxide (SiO_2)		56.59%				
Aluminium Oxide (Al_2O_3)		23.89%				
Iron Oxide (Fe_2O_3)		4.82%				
Sum of SiO_2, Al_2O_3 and Fe_2O_3		85.30%	50 Min.	70 Min.	50 Min.	70 Min.
Magnesium Oxide (MgO)		1.83%				
Sulfur Trioxide (SO_3)		0.39%	5.0 Max.	5.0 Max.	5.0 Max.	5.0 Max.
Sodium Oxide (Na_2O)		0.24%				
Potassium Oxide (K_2O)		1.03%				
Total Alkalis as Na_2O		0.92%				
Calcium Oxide (CaO)		9.42%				
PHYSICAL ANALYSIS						
Moisture Content		0.00%	3.0 Max.	3.0 Max.	3.0 Max.	3.0 Max.
Loss on Ignition		0.23%	6.0 Max.	6.0 Max.	5.0 Max.	5.0 Max.
Fineness: Amount retained on 325 sieve %		19.45%	34% Max.	34% Max.	34% Max.	34% Max.
Water Requirement, % Control		95%	105% Max.	105% Max.	105% Max.	105% Max.
Specific Gravity		2.29				
Autoclave Soundness, %		0.03%	0.8% Max.	0.8% Max.	0.8% Max.	0.8% Max.
Strength Activity Index With Portland cement	7 Days	76.60%	75% Min.	75% Min.	75% Min.	75% Min.
	28 Days	89.50%	75% Min.	75% Min.	75% Min.	75% Min.
Loose Dry Bulk Density, lb/cu. ft		69.70%				

Table A-3 Composition of Class “F” Fly Ash (1.29%)

			ASTM C-618-08 SPECIFICATIONS		AASHTO M 295 SPECIFICATION	
CHEMICAL ANALYSIS						
			CLASS C	CLASS F	CLASS C	CLASS F
Silicon Dioxide (SiO_2)		54.70%				
Aluminium Oxide (Al_2O_3)		29.00%				
Iron Oxide (Fe_2O_3)		6.74%				
Sum of SiO_2, Al_2O_3 and Fe_2O_3		90.44%	50 Min.	70 Min.	50 Min.	70 Min.
Magnesium Oxide (MgO)		0.80%				
Sulfur Trioxide (SO_3)		0.10%	5.0 Max.	5.0 Max.	5.0 Max.	5.0 Max.
Sodium Oxide (Na_2O)		0.25%				
Potassium Oxide (K_2O)		2.47%				
Total Alkalis as Na_2O		1.88%				
Calcium Oxide (CaO)		1.29%				
PHYSICAL ANALYSIS						
Moisture Content		0.09%	3.0 Max.	3.0 Max.	3.0 Max.	3.0 Max.
Loss on Ignition		2.72%	6.0 Max.	6.0 Max.	5.0 Max.	5.0 Max.
Fineness: Amount retained on 325 sieve %		20.90%	34% Max.	34% Max.	34% Max.	34% Max.
Water Requirement, % Control		97.50%	105% Max.	105% Max.	105% Max.	105% Max.
Specific Gravity		2.23				
Autoclave Soundness, %		0.03%	0.8% Max.	0.8% Max.	0.8% Max.	0.8% Max.
Strength Activity Index With Portland cement	7 Days	70.70%	75% Min.	75% Min.	75% Min.	75% Min.
	28 Days	85.70%	75% Min.	75% Min.	75% Min.	75% Min.
Loose Dry Bulk Density, lb/cu. ft		69.70%				

Appendix B

Mix Designs

Table B-1 Mix Designs (A1 through A11, B1 through B4)

Mix #		*Fly Ash (lb/ft^3)*	*Aggregate (lb/ft^3)*			*Sodium Hydroxide Solution (lb/ft^3)*	*Sodium Silicate Solution (lb/ft^3)*	*Conc. Of NaOH (M)*	*SP (lb/ft^3)*	*Added Water (lb/ft^3)*	*Curing*		
			3/8	*5/8*	*Sand*						*Time (hrs.)*	*Temp. (°F)*	*Method*
A	A1	25.5	50	15	50	2.6	6.5	14	0.4	1	24	115	Steam
	A2	25.5	50	15	50	2.6	6.5	14	0.4	1	24	131	Oven
	A3	25.5	50	15	50	2.6	6.5	14	0.4	1	24	158	Oven
	A4	25.5	80	-	35	2.6	6.5	14	0.4	1	24	115	Steam
	A5	25.5	80	-	35	2.6	6.5	14	0.4	1	24	131	Oven
	A6	25.5	80	-	35	2.6	6.5	14	0.4	1	24	158	Oven
	A7	25.5	60	-	55	2.6	6.5	14	0.4	1	24	115	Steam
	A8	25.5	60	-	55	2.6	6.5	14	0.4	1	24	131	Oven
	A9	29.1	69.25	23.08	39.53	2.95	7.4	14	0.44	0.49	24	115	Steam
	A10	29.1	69.25	23.08	39.53	2.95	7.4	14	0.44	0.49	24	131	Oven
	A11	29.1	69.25	23.08	39.53	2.95	7.4	14	0.44	0.49	24	158	Oven
B	B1	25.5	40	40	35	2.6	6.5	8	0.4	1	24	158	Oven
	B2	29.1	69.25	23.1	39.5	2.9	7.4	8	0.4	0.5	24	75	Steam
	B3	29.1	69.25	23.1	39.5	2.9	7.4	8	0.4	0.5	24	Room	Room
	B4	29.1	69.25	23.1	39.5	2.9	7.4	8	0.4	0.5	24	90	Oven

Note: A: 14.14% CaO Fly Ash B: 9.42% CaO Fly Ash C: 1.29% CaO Fly Ash

Table B-2 Mix Designs (B5 through B20)

Mix #		*Fly Ash (lb/ft^3)*	*Aggregate (lb/ft^3)*			*Sodium Hydroxide Solution (lb/ft^3)*	*Sodium Silicate Solution (lb/ft^3)*	*Conc. Of NaOH (M)*	*SP (lb/ft^3)*	*Added Water (lb/ft^3)*	*Curing*		
			3/8	*5/8*	*Sand*						*Time (hrs.)*	*Temp. (°F)*	*Method*
B	B5	29.1	69.25	23.1	39.5	2.9	7.4	8	0.4	0.5	24	115	Steam
	B6	29.1	69.25	23.1	39.5	2.9	7.4	8	0.4	0.5	24	131	Oven
	B7	29.1	69.25	23.1	39.5	2.9	7.4	8	0.4	0.5	24	158	Oven
	B8	29.1	69.25	23.1	39.5	2.9	7.4	8	0.4	0.5	24	170	Oven
	B9	25.5	50	15	50	2.6	6.5	12	0.4	1	24	115	Oven
	B10	25.5	50	15	50	2.6	6.5	12	0.4	1	24	131	Oven
	B11	25.5	50	15	50	2.6	6.5	12	0.4	1	48	131	Oven
	B12	25.5	80	-	35	2.6	6.5	12	0.4	1	24	158	Oven
	B13	25.5	50	15	50	2.6	6.5	12	0.4	1	48	158	Oven
	B14	24.8	38.9	38.9	34	2.6	6.3	14	0.4	6.14	24	75	Steam
	B15	24.8	38.9	38.9	34	2.6	6.3	14	0.8	2.2	24	90	Oven
	B16	24.8	38.9	38.9	34	2.6	6.3	14	0.6	3.1	24	115	Steam
	B17	24.8	38.9	38.9	34	2.6	6.3	14	0.6	3.1	24	115	Oven
	B18	24.8	38.9	38.9	34	2.6	6.3	14	0	6.1	24	158	Oven
	B19	25.5	50	15	50	2.6	6.5	14	0.4	1	24	90	Oven
	B20	25.5	50	15	50	2.6	6.5	14	0.4	1	24	115	Oven

Note: A: 14.14% CaO Fly Ash B: 9.42% CaO Fly Ash C: 1.29% CaO Fly Ash

Table B-3 Mix Designs (B21 through B34)

Mix #		Fly Ash (lb/ft^3)	Aggregate (lb/ft^3)			Sodium Hydroxide Solution (lb/ft^3)	Sodium Silicate Solution (lb/ft^3)	Conc. Of NaOH (M)	SP (lb/ft^3)	Added Water (lb/ft^3)	Curing		
			3/8	5/8	Sand						Time (hrs.)	Temp. (°F)	Method
B	B21	25.5	50	15	50	2.6	6.5	14	0.4	1	24	131	Oven
	B22	25.5	50	15	50	2.6	6.5	14	0.4	1	48	131	Oven
	B23	25.5	50	15	50	2.6	6.5	14	0.4	1	24	158	Oven
	B24	25.5	80	-	35	2.6	6.5	14	0.4	1	24	75	Steam
	B25	25.5	80	-	35	2.6	6.5	14	0.4	1	24	90	Oven
	B26	25.5	80	-	35	2.6	6.5	14	0.4	1	24	115	Steam
	B27	25.5	80	-	35	2.6	6.5	14	0.4	1	24	131	Oven
	B28	25.5	80	-	35	2.6	6.5	14	0.4	1	24	158	Oven
	B29	25.5	60	-	55	2.6	6.5	14	0.4	1	24	115	Steam
	B30	25.5	60	-	55	2.6	6.5	14	0.4	1	24	131	Oven
	B31	25.5	60	-	55	2.6	6.5	14	0.4	1	24	158	Oven
	B32	25.5	50	15	50	2.6	6.5	17	0.4	1	24	75	Steam
	B33	25.5	50	15	50	2.6	6.5	17	0.4	1	24	115	Steam
	B34	25.5	50	15	50	2.6	6.5	17	0.4	1	24	115	Oven

Note: A: 14.14% CaO Fly Ash B: 9.42% CaO Fly Ash C: 1.29% CaO Fly Ash

Table B-4 Mix Designs (B35 through B38)

Mix #		Fly Ash (lb/ft^3)	Aggregate (lb/ft^3)			NaOH Sol^n (lb/ft^3)	Na$_2$SiO$_3$ Sol^n (lb/ft^3)	Conc. Of NaOH (M)	SP (lb/ft^3)	Added Water (lb/ft^3)	Curing			Extra additive	
			3/8	5/8	Sand						Time (hrs.)	Temp. (°F)	Method	Steel Fiber (lb/ft^3)	Crumb Rubber (% by vol. of sand)
B	B35	25.5	50	15	50	2.6	6.5	14	0.4	1	24	115	Steam	1.48	-
	B36	25.5	50	15	50	2.6	6.5	14	0.4	1	24	158	Oven	1.48	-
	B37	25.5	80	-	35 - 2.6 =32.4	2.6	6.5	14	0.4	-	24	75	Steam	-	7.5% of 35= 2.6
	B38	25.5	80	-	35 - 5.25 =29.75	2.6	6.5	14	0.4	-	24	Room	Room	-	15% of 35= 5.25

Table B-5 Mix Designs (C1 through C4)

Mix #		Fly Ash (lb/ft^3)	Aggregate (lb/ft^3)			Sodium Hydroxide Solution (lb/ft^3)	Sodium Silicate Solution (lb/ft^3)	Conc. Of NaOH (M)	SP (lb/ft^3)	Added Water (lb/ft^3)	Curing		
			3/8	5/8	Sand						Time (hrs.)	Temp. (°F)	Method
C	C1	25.5	50	15	50	2.6	6.5	12	0.4	1	48	131	Oven
	C2	25.5	50	15	50	2.6	6.5	14	0.4	1	48	131	Oven
	C3	25.5	80	-	35	2.6	6.5	8	0.4	-	24	158	Oven
	C4	25.5	80	-	35	2.6	6.5	14	0.4	-	24	158	Oven

Note: A: 14.14% CaO Fly Ash B: 9.42% CaO Fly Ash C: 1.29% CaO Fly Ash

Appendix C

Compressive Strength of Mix Designs

Table C-1 Compressive Strength of Mix Design (A1 through A11, B1 through B16)

Mix #		*Compressive Strength (ksi)*			
		1	*3*	*7*	*28*
A	A1	3.39	4.48	5.44	-
	A2	3.75	4.34	4.73	-
	A3	1.81	2.08	2.42	-
	A4	4.22	4.31	4.48	-
	A5	3.11	3.39	4.06	-
	A6	2.34	2.76	2.85	-
	A7	4.21	4.23	4.24	-
	A8	2.82	3.57	3.86	-
	A9	1.72	3.35	3.55	-
	A10	1.82	2.48	2.92	-
	A11	1.54	1.99	2.09	-
B	B1	-	1.97	2.24	2.71
	B2	-	-	1.14	1.83
	B3	-	-	3.50	4.04
	B4	1.54	1.99	2.09	2.34
	B5	1.72	3.35	3.55	3.84
	B6	1.82	2.48	2.92	3.49
	B7	3.32	3.47	4.10	4.24
	B8	-	2.25	4.12	5.63
	B9	1.89	2.30	2.41	2.84
	B10	1.60	1.79	2.58	-
	B11	3.55	4.88	5.44	5.51
	B12	4.23	4.24	4.90	5.36
	B13	-	1.55	1.89	2.48
	B14	-	1.00	1.16	1.26
	B15	0.87	1.92	2.36	2.46
	B16	2.55	2.44	4.00	-

Note: A: 14.14% CaO Fly Ash B: 9.42% CaO Fly Ash C: 1.29% CaO Fly Ash

Table C-2 Compressive Strength of Mix Design (B21 through B38, C1 through C4)

Mix #		*Compressive Strength (ksi)*			
		1	*3*	*7*	*28*
B	B17	2.17	2.71	4.18	-
	B18	-	1.89	2.03	2.48
	B19	1.81	2.08	2.42	-
	B20	3.40	4.48	4.74	5.46
	B21	3.75	4.35	5.44	5.68
	B22	-	3.97	5.60	6.03
	B23	5.68	6.70	7.13	7.23
	B24	-	0.88	1.64	2.42
	B25	2.34	2.76	2.85	3.17
	B26	4.22	4.31	4.48	4.64
	B27	3.11	3.39	4.06	-
	B28	3.25	5.03	5.65	-
	B29	4.21	4.23	4.24	4.53
	B30	2.82	3.57	3.86	4.38
	B31	3.25	4.66	5.11	5.71
	B32	-	1.23	1.78	2.82
	B33	1.02	1.65	-	-
	B34	5.19	5.91	-	-
	B35	-	2.78	3.10	3.50
	B36	-	3.30	4.25	-
	B37	1.40	1.47	1.60	2.50
	B38	-	1.70	2.50	2.80
C	C1	4.17	4.34	4.71	-
	C2	3.97	4.69	6.03	-
	C3	4.45	4.83	4.83	-
	C4	1.20	1.34	1.50	-

Note:	A:	14.14% CaO Fly Ash	B:	9.42% CaO Fly Ash	C:	1.29% CaO Fly Ash

Appendix D

Maximum Compressive Strength

From the different types of Mixes prepared for this Research

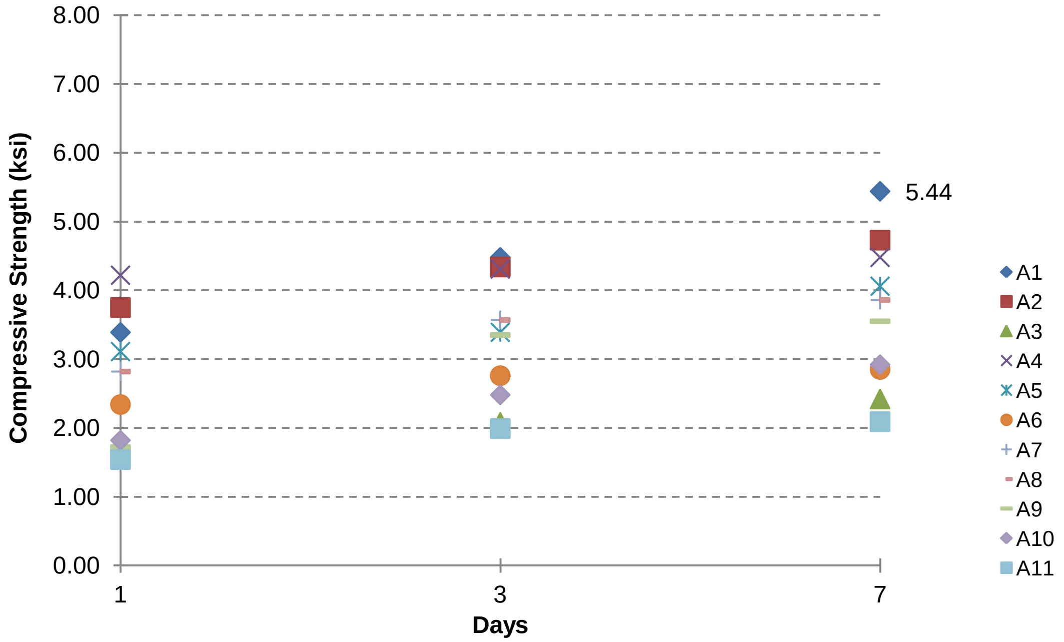


Figure D-1 Compressive Strength of Mix A

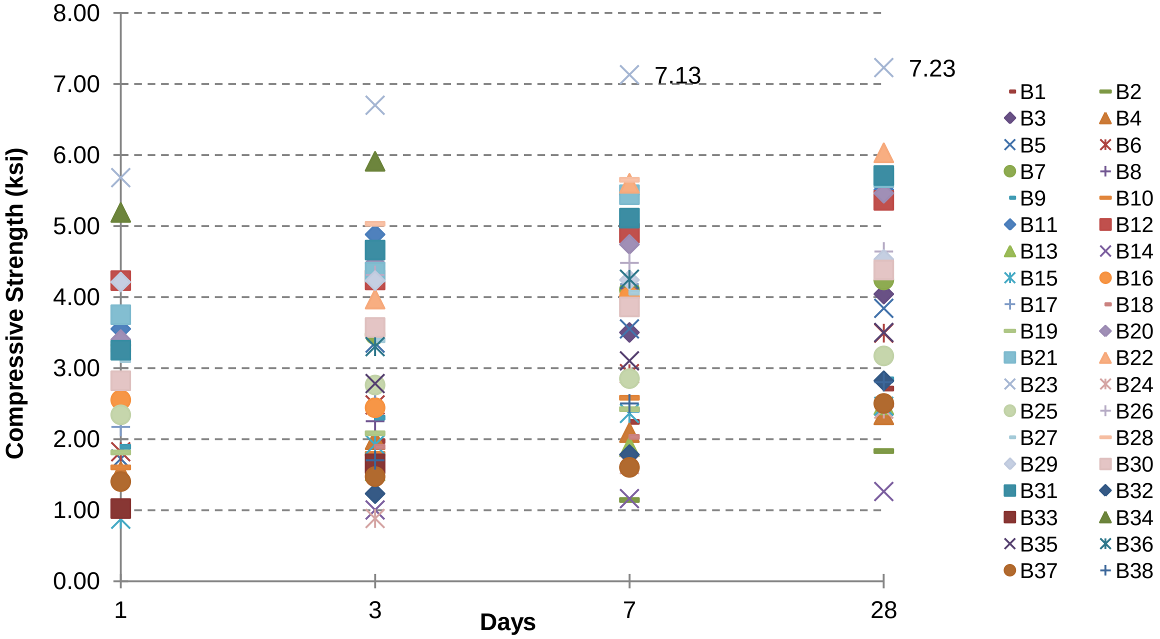


Figure D-2 Compressive Strength of Mix B

Note:

A: 14.14% CaO Fly Ash

B: 9.42% CaO Fly Ash

C: 1.29% CaO Fly Ash

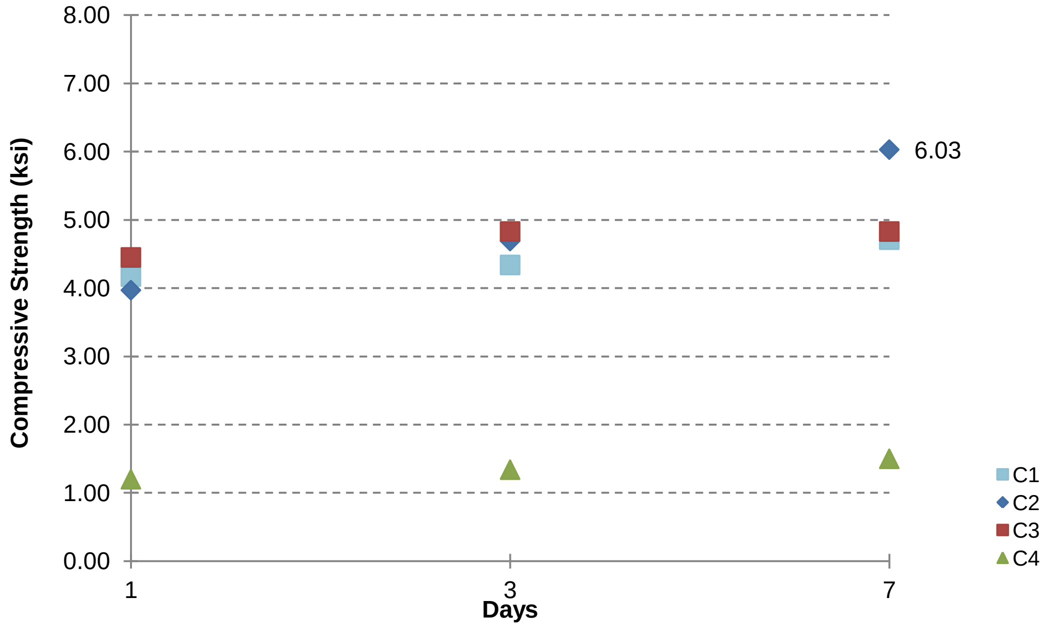


Figure D-3 Compressive Strength of Mix C

Note:

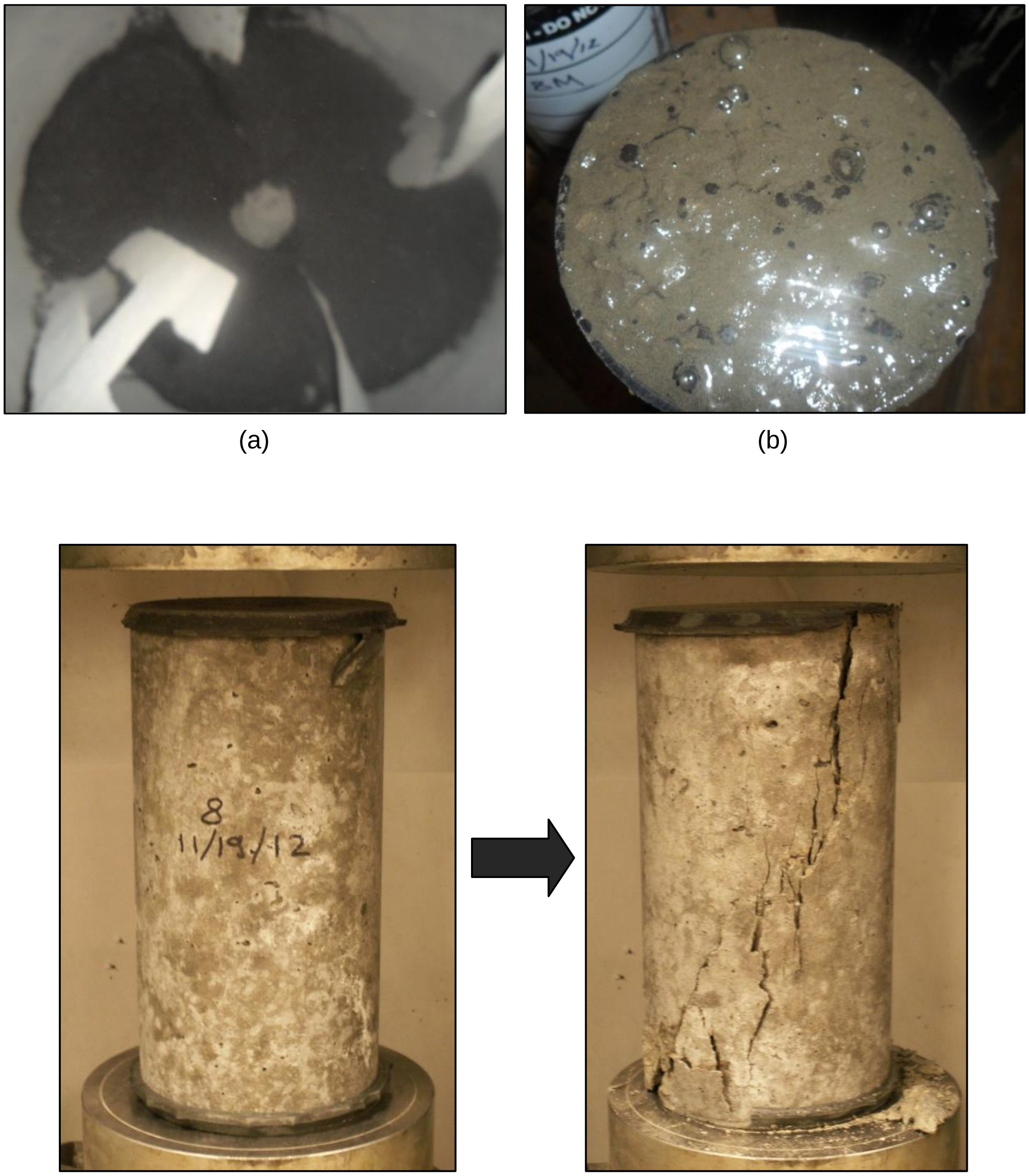
A: 14.14% CaO Fly Ash

B: 9.42% CaO Fly Ash

C: 1.29% CaO Fly Ash

Appendix E

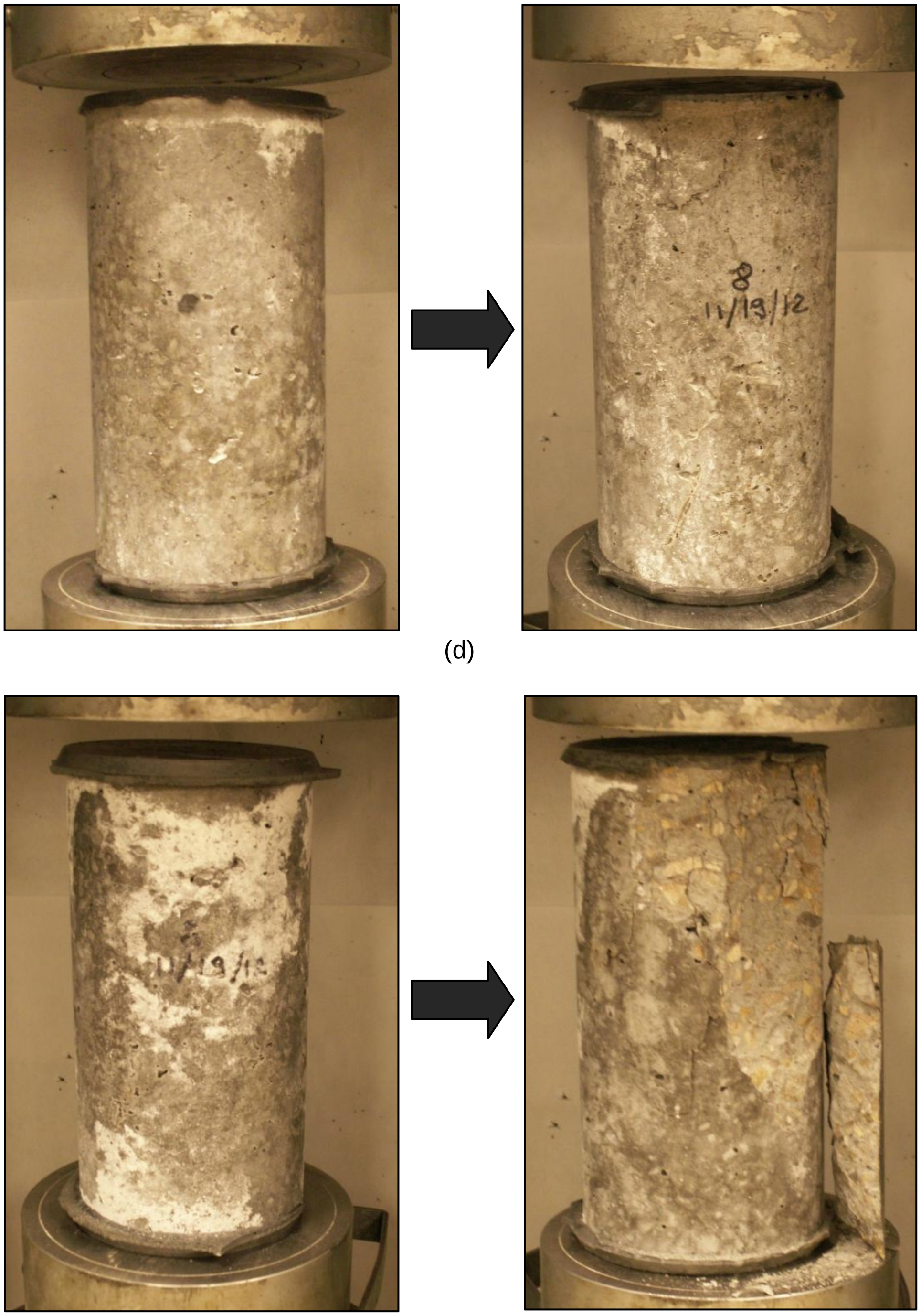
Experimental Photographs



(a) (b)

(c)

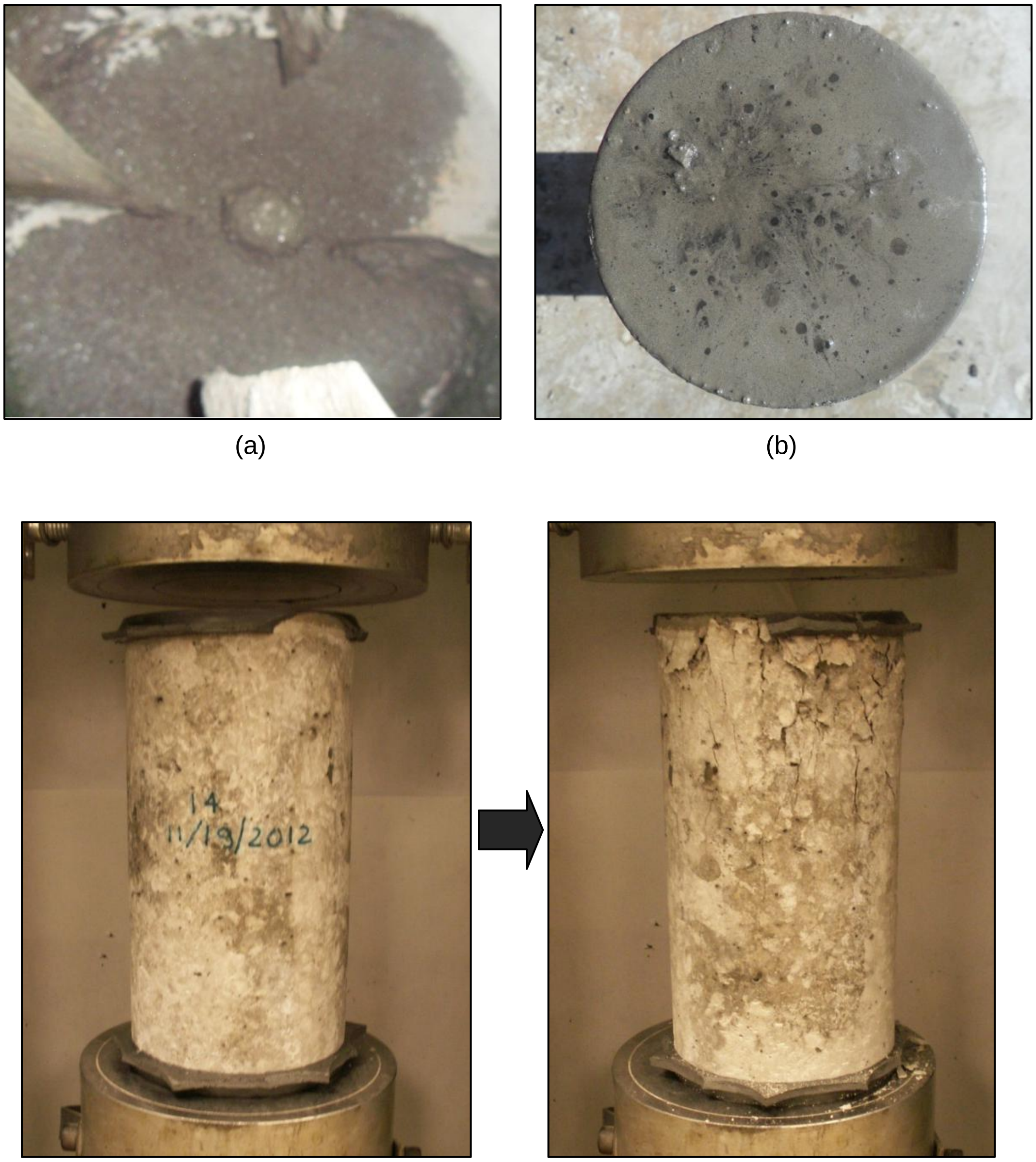
Figure E-1 (a) Geopolymer Concrete Mix (b) Plan View of Casted Cylinder (c) Failure Pattern on 1 Day Testing of Cylinder prepared from 1.29% CaO Fly ash of 8M concentration of Sodium Hydroxide Solution (Appendix B – Mix C3)



(d)

(e)

Figure E-1 (d) Failure Pattern on 3 Days Testing (e) Failure Pattern on 7 Days Testing of Cylinder prepared from 1.29% CaO Fly ash of 8M concentration of Sodium Hydroxide Solution (Appendix B – Mix C3)



(a) (b)

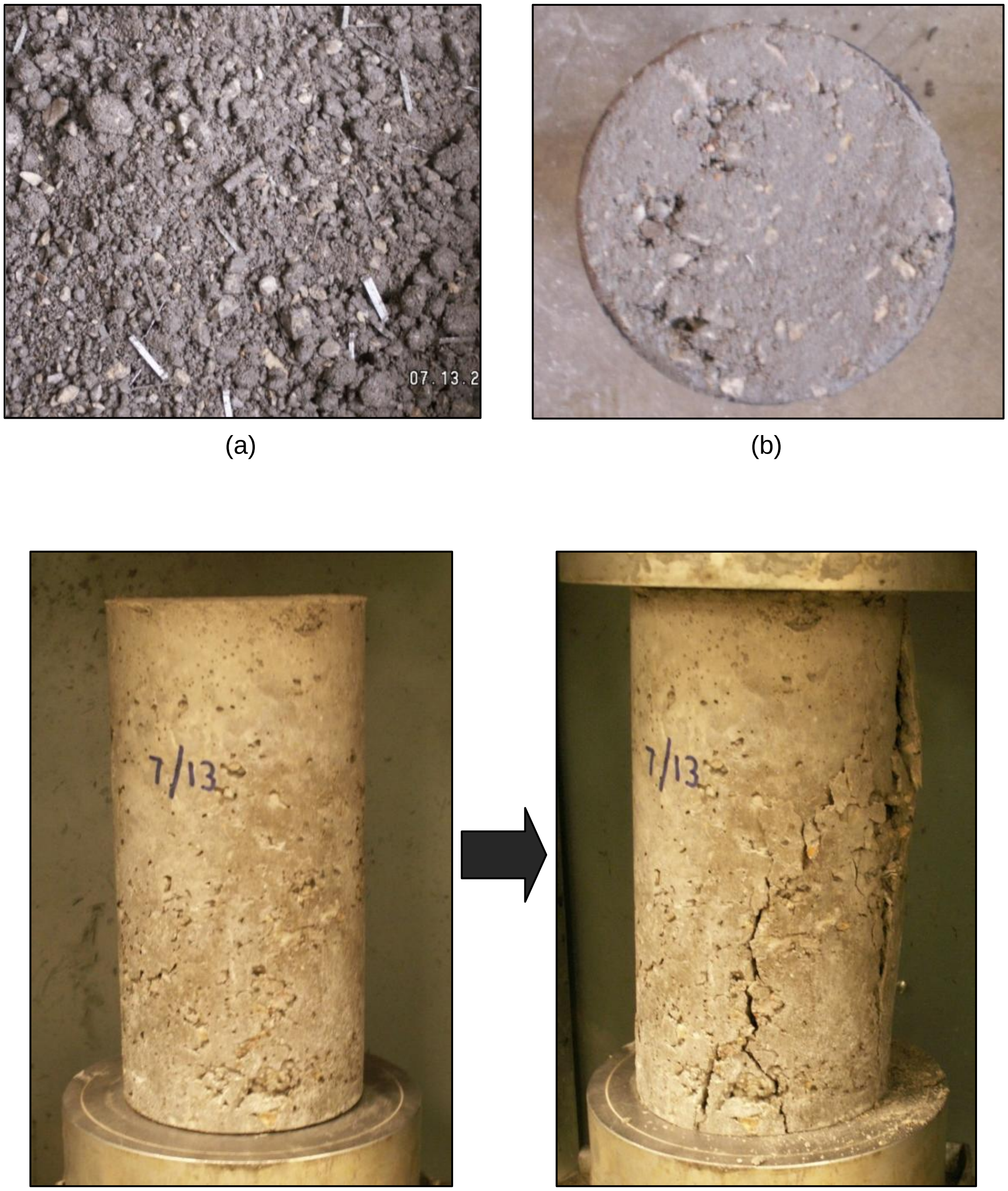
(c)

Figure E-2 (a) Geopolymer Concrete Mix (b) Plan View of Casted Cylinder (c) Failure Pattern on 3 Days Testing of Cylinder prepared from 1.29% CaO Fly ash of 14M concentration of Sodium Hydroxide Solution (Appendix B – Mix C4)

(d)

Figure E-2 (d) Failure Pattern on 7 Days Testing of Cylinder prepared from 1.29% CaO Fly ash of 14M concentration of Sodium Hydroxide Solution (Appendix B – Mix C4)

Figure E-3 Geopolymer Concrete Mix with Crumb Rubber

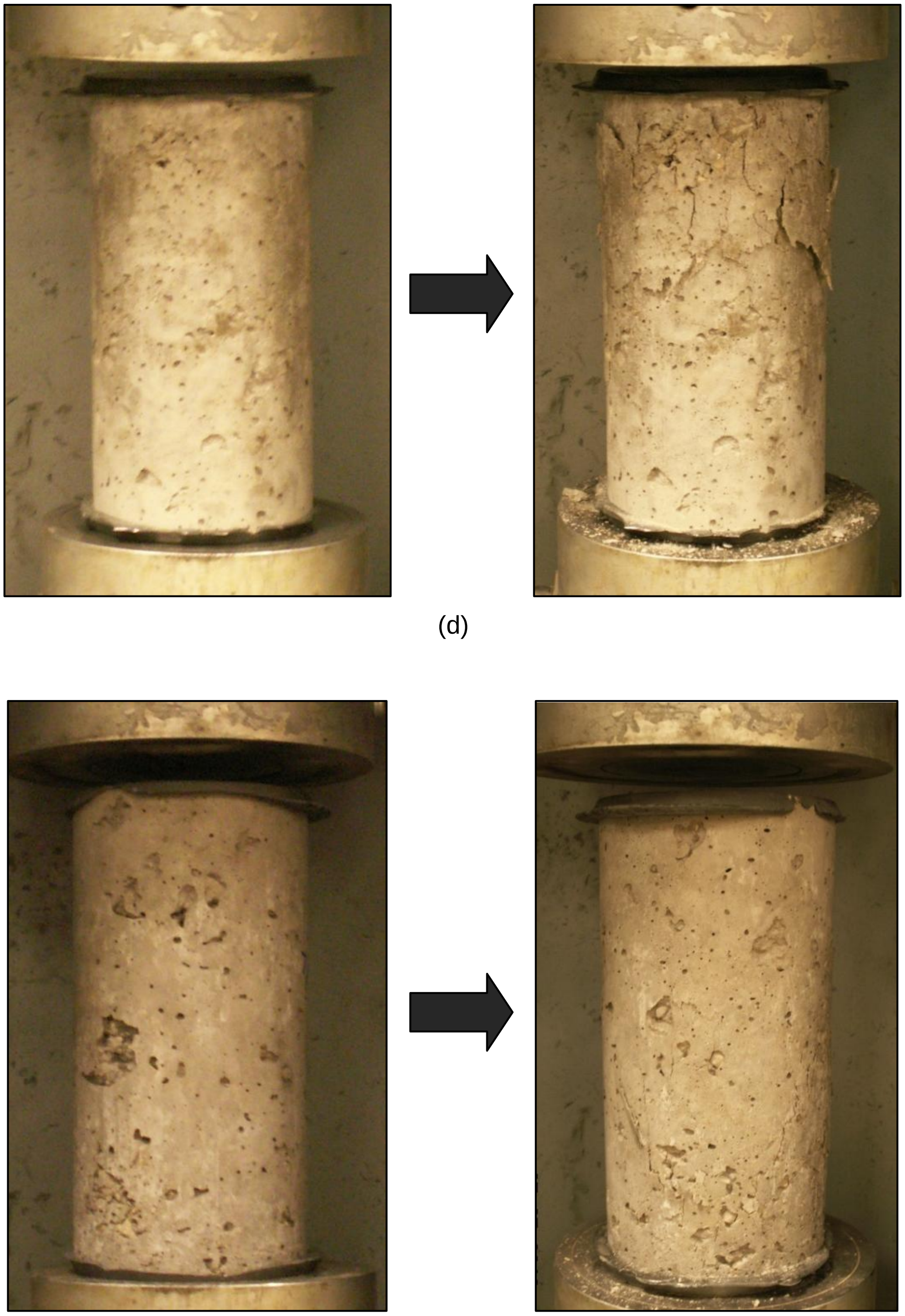


(a)

(b)

(c)

Figure E-4 (a) Geopolymer Concrete Mix (b) Plan View of Casted Cylinder (c) Failure Pattern on 3 Days Testing of Cylinder prepared from 9.42% CaO Fly ash containing Steel Fibers (Appendix B – Mix B36)



(d)

(e)

Figure E-4 (d) Failure Pattern on 7 Days Testing (e) Failure Pattern on 28 Days Testing of Cylinder prepared from 9.42% CaO Fly ash containing Steel Fibers (Appendix B – Mix B36)

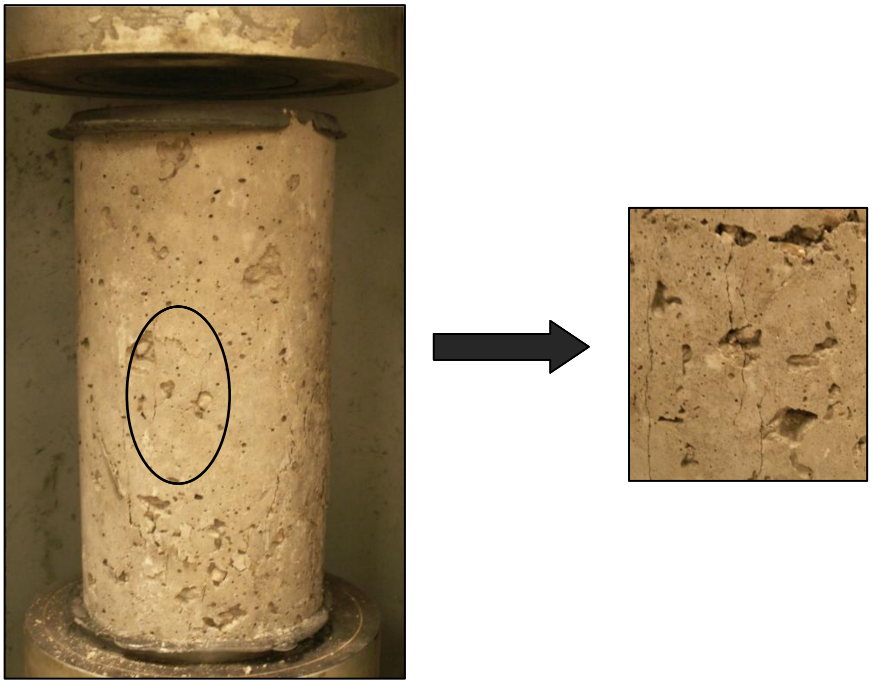


Figure E-5 Enlarged View of Failure Pattern on 28 Days Testing of Cylinder prepared from 9.42% CaO Fly ash containing Steel Fibers (Appendix B – Mix B36)

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