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# Cost and Fuel Usage Optimization of Activating Solution Based Silica Fume Geopolymer Concrete

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Cost and fuel usage  
optimization of activating solution based silica fume geopolymer concrete

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## **DEDICATION**

To my parents, for their endless love, support, and encouragement, to my uncle Saad Shiaa for his invaluable advice and support, to Dr. Kealy Carter for her invaluable support and encouragement, and to my professor at the University of South Carolina and all my friends.

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## ABSTRACT

Development of sustainable construction materials has been the focus of research efforts worldwide in recent years. Concrete is a major construction material; hence, finding alternatives to ordinary Portland cement is of extreme importance due to high levels of carbon dioxide emissions associated with its manufacturing process. Geopolymer concrete is a potential solution; however, concerns about the high cost and the low real fuel energy efficiency are obstacles against its increase in the market share.

In this thesis, the current cost and fuel (thermal energy) usage are calculated. In addition, the cost and fuel usage were optimized based on previous experimental results. The results show that geopolymer concrete cost can be reduced using Portland cement in low percentage replacement (5-35%). The required fuel usage (thermal energy) for producing geopolymer concrete was lower than Portland cement. Using Portland cement and reducing sodium hydroxide concentration not only reduce the cost of geopolymer concrete but also reduce the fuel usage. Based on the results of the study, the sodium hydroxide and silica fume have a significant role in the fuel usage and the cost. Three new mixtures were proposed to reduce the cost. Additionally, the fuel usage was 30% lower than Portland cement. Marketing and communication plans showed that geopolymer concrete industries could be profitable because geopolymer concrete can be used for varied civil engineering applications including sidewalks, concrete panels, etc.

The best locations to start the business were proposed, including some cities in the north east or east of the United States such as Cleveland, Milwaukee, and Charlotte. Internationally, China was considered the best place to start the business due to the availability of raw materials and affordable prices.



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CHAPTER 1  
INTRODUCTION

Numerous amounts of Portland cement concrete are produced annually. For instance, around ten billion metric tons of concrete are produced worldwide and over 500 million tons in the United States alone [1]. In other words, two tons of conventional concrete were produced in the United States, for each family consisting of a man, woman, and child. The Portland cement production is predicted to be around two billion tons by 2050, in the United States alone, which means it is four times higher than the level in 1990 [2]. Nowadays, Portland cement factories are responsible for 7% of total worldwide CO<sub>2</sub> emissions [3]. It has been stated that each ton of Portland cement produces approximately one ton of CO<sub>2</sub> [4]. This extraordinary amount of cement and CO<sub>2</sub> emissions has elevated global awareness and prompted scientists to think about alternative, sustainable concrete and cement options.

Geopolymer concrete and cement is a sustainable product. It is a mixture of aluminate silicate source materials such as fly ash, blast furnace slag or metakaolin, and an activating solution including either sodium silicate, sodium hydroxide [5-8], or silica fume, sodium hydroxide and water [9]. Geopolymer concrete has been shown to have good resistance against sulfate attack and acid, high early and final compressive strength, and high resistance to fire, in the presence of external heat [10-18]. Recently, good compressive strength has been achieved in ambient conditions [19].



Geopolymer concrete can be considered as an alternative concrete product to conventional concrete because it not only reduces CO<sub>2</sub> emissions [20], but it also utilizes waste materials such as fly ash.

Several research projects have been conducted to investigate the effect of sodium hydroxide concentration on the mechanical and chemical properties of geopolymer concrete. Chindaprasirt and Chalee studied the effect of sodium hydroxide concentration on chloride penetration and steel corrosion of fly ash based geopolymer concrete. Both chloride penetration and corrosion were decreased when sodium hydroxide increased [21]. The compressive strength and reaction products were found to be strongly related to sodium hydroxide concentration [22-25]. Other researchers found the setting time, conductivity, porosity, slump, flexural strength, and tensile strength were improved when sodium hydroxide concentration increased. As described above, several tests have been conducted to investigate the effect of sodium hydroxide on varied chemical and mechanical properties [26-28], while its effect on the cost and fuel (thermal energy) usage has not been investigated with different sodium hydroxide concentrations.

Although much research has been dedicated to omitting the use of external heat in the geopolymer concrete curing and aging periods, external heat still plays a dominant role in geopolymer concrete production. For instance, many researchers have investigated geopolymer concrete performance at ambient conditions [29-32]. It has been discovered that early compressive strength, elastic modulus, and flexural strength properties were reduced when the elevated external heat was removed [29]. The ambient curing conditions accompanied with moisture curing showed early compressive strength enhancement compared with external heat-cured specimens [30]. The early compressive

strength and initial setting time were improved when a small proportion of ordinary Portland cement was used [31]. The bond strength of geopolymer concrete at ambient and elevated temperatures was investigated, and the result showed bonding strength was decreased at an ambient curing temperature [32]. Mechanical and structural properties, fracture behavior, the role of microwave radiation, thermal behavior, compressive strength and transport properties of geopolymer concrete, mortar or paste were investigated. The results showed that the geopolymer concrete behaved better when the external heat was applied [33-45]. On the other hand, there is no specific research investigating the effect of elevated heat on the cost of geopolymer concrete and fuel (thermal usage) energy in the United States.

The cost and CO<sub>2</sub> emissions, the latter of which are related to the energy consumption of the raw materials and geopolymer production, have been investigated worldwide by few researchers. McLellan et al. have investigated cost and carbon emissions, in Australia, for geopolymer paste in comparison with Portland cement; the cost was 93-139%, while a 44-64% reduction in greenhouse gas emissions was achieved in comparison with Portland cement [46]. Compared to Portland cement, some researchers have claimed that there is slightly less carbon emissions, but others have claimed it is higher in the case of geopolymer where concrete was used [47, 48]. However, their assumptions are suspicious because the external heat was assumed to be primary, and the CO<sub>2</sub> emissions of sodium silicate was not calculated correctly [49]. It was shown that 80% of the total cost of geopolymer was contributed by the activating solution [50]. Yang et al. showed that the reduction in CO<sub>2</sub> emissions was between 55-75% when geopolymer concrete was compared to Portland cement [51]. No new mix

designs have been proposed to reduce the cost of geopolymer concrete, and the marketing and communication plans have not been discussed.

In this thesis, fly ash-based geopolymer concrete, specifically with an activating solution that is a combination of silica fume, sodium hydroxide, and water, will be the main focus. Cost and fuel (thermal energy) usage will be calculated based on the current data. The case studies will be held mainly in the United States. The effect of sodium hydroxide, external heat on the cost and fuel (thermal energy) usage of fly ash-based geopolymer concrete will be assessed. Based on the observed results, new mix designs will be introduced for reducing the cost and fuel usage of geopolymer concrete. Eliminating the need for external heat will be tackled. In addition, marketing and communication plans will be set depending on the estimated price and availability of raw materials in the United States.

CHAPTER 2  
BACKGROUND OF COAL COMBUSTION PRODUCTS

The primary use of coal is to fuel electric power stations. It is considered the primary energy source in many large countries. For example, the percentage of energy which comes from coal is 79% in China, 69% in India, and 49% in the United States [52]. As a result, the total coal combustions worldwide are 780 million metric tons per year. Only 53% of the total coal combustion products are utilized globally, and the rest will go to the disposal sites, which are usually at an electric power station. Figure 2.1 shows the coal combustion products and their utilization per year worldwide. From Figure 2.1, in China, which is the top coal producer, the coal ash combustion production is around 400 million tons per year, and the utilization is around 270 million tons, which means 130 million tons are not utilized. The annual United States coal combustion production is around 120 million tons, and the utilization is around 55 million tons [65].

Some studies have shown that coal usage for producing energy will be increased due to two reasons: cost and widely distributed coal reserves. The cost of coal is estimated to be the lowest cost among energy sources including wind, natural gas, and nuclear energy. Peabody Energy incorporation states that the energy produced by coal is estimated to be 15-50% less costly than wind energy, 25%-45% less than natural gas, and 15% less than nuclear energy [53]. Coal reserves are widely distributed in developed countries unlike other energy resources such as natural gas and oil, which are concentrated in the Middle East [54].

Figure 2.2 shows coal reserves for the United States and other countries [55]. With more than 220 billion metric tons, the United States has numerous amount of coal reserves. This vast amount of coal reserves leads to the fact that coal will be one of the main energy sources for more than the next hundred years into the future. Unfortunately, fly ash production in the United States has had some shortages in recent years due to the federal government's regulations for reducing CO<sub>2</sub> emissions. However, based on the most recent interview with Dr. Adams Thomas, who is executive director of the American Coal Ash Association (ACAA), the future of fly ash is secure and its production will increase [76]. The price of natural gas will increase; hence, coal will be dispatched at a higher rate. In addition, most of the coal plants are well-equipped to meet government regulations, which will increase the fly ash productions again [76].

In the United States, coal combustion products' rate of utilization to production is roughly around 40% [56]. The American Coal Ash Association (ACAA) reported in 2012 that only 44.5% of the fly ash and 38.8% of the bottom ash production were utilized [56]. In addition, the Electric Power Research Institute (EPRI) showed that 60% of the coal ash products are kept in disposal sites in the United States [57]. Disposal sites have a potential impact on humans, animals, and the environment.

By assuming the yearly production rate of 110 million metric tons, and a disposal rate of 60%, a rough, simple calculation shows the amount of disposal coal combustion products that have been stored since 1971 until the current time. Therefore, the stored fly ash would be at least 2970 metric tons. As shown in Figure 2.2, the United States has an enormous amount of coal reserves, which means more coal combustion products will be disposed of, in the future, likely around electric power stations [57]. This

amount of discarded coal combustion products should raise awareness about finding an objective way, such as geopolymers concrete, to utilize these products. Figure 2.3 and Figure 2.4 show the United States map of coal power plants [58, 59]. These maps can help to predict where most of these products will be deposited, and they are helpful to predict the best location for constructing geopolymers concrete industries. As shown in Figures 2.3 and 2.4, most of the coal combustion products are concentrated in the Northeast and Midwest (East North Central) areas of the United States including Wisconsin, Michigan, Illinois, Indiana, and Ohio.

The coal combustion products are a combination of fly ash, bottom ash, flue gas, and boiler slag. Table 1.1 explains each product briefly, and shows their percentage as well [60-63]. With 57% of fly ash and 17% of bottom ash, it seems the majority of the coal combustion products is fly ash, with bottom ash coming in second [62]. Therefore, focusing on the fly ash and bottom ash will help to reduce coal combustion disposal.

The coal combustion products are usually deposited in a landfill or an impoundment close to electric power station sites. There are more than six hundred electric power station sites around the United States. There are some environmental issues related to coal combustion disposals such as leaching of mercury into the soil, windblown ash, and radioactivity. For example, according to the problem related to coal combustion waste in Tennessee in December 2008. Tennessee Valley Authority's (TVA's) Kingston plant released 1.1 billion gallons of coal fly ash slurry (toxic waste) into the soil [63]. More than 300 acres was damaged and there were negative effects on homes and prosperity. In addition, the toxic waste was released to the neighboring river and killed several animals including fish [63].

In conclusion, there is a huge amount of coal combustion products, are stored and disposed of in the United States. These products have a potential risk on humans, animals, and plants because the toxic materials and fly ash will effect them if it was stored in underground or it stored outside (on the ground). Because coal ash combustion products are continuously increasing and there are already massive amounts disposed amounts, geopolymer concrete becomes one of the potential solutions. It not only utilizes such waste materials, it also converts them to useful products. The only concern for the geopolymer concrete is the cost and required thermal energy in comparison with Portland cement. The issue of the cost and thermal energy will be addressed in this thesis, as well as finding the dominant material's effect on the of cost fuel usage; hence, finding and proposing ways to optimize the cost and thermal energy.



**Tables:**

Table 2.1 Coal combustion and its materials descriptions [60-63]

| Waste Type                              | Description  | Percentage of Total Generated |
|---|--|-------------------------------|
| Fly Ash                                 | A product of burning finely ground coal in a boiler to produce electricity. It is generally captured in the plant's chimney or stack through a particulate control device (e.g., electrostatic precipitators or fabric filters). It consists mostly of silt-sized and clay-sized glassy spheres, giving it a consistency somewhat like talcum powder.  | 57%                           |
| Flue Gas Desulfurization (FGD) Material | Flue gas desulfurization (FGD) is a chemical process implemented in order to meet emission requirements in the Clean Air Act applicable to sulfur dioxide (an emission associated with acid rain). The goal of the process is to chemically combine the sulfur gases released in coal combustion by reacting them with a sorbent, such as limestone (calcium carbonate), lime (calcium oxide), or ammonia. Depending on the FGD process used at the plant, the material may be a wet sludge or a dry powder. The wet sludge is likely predominantly calcium sulfite or calcium sulfate. The dry material generally consists of a mixture of sulfites and sulfates. | 24%                           |
| Bottom Ash                              | A coarse, gritty material, these agglomerated ash particles are those that are too large to be carried in flue gases. They impinge on the furnace walls or fall through open grates to an ash hopper at the bottom of the furnace. The material is taken from the bottom of the boiler furnace either in its dry form or as a slurry (via the addition of water). It has a porous surface structure and is coarse, with grain sizes spanning from fine sand to fine gravel.  | 17%                           |
| Boiler Slag                             | This type of ash collects at the base of certain furnaces that are quenched with water. When molten slag comes in contact with quenching water, it fractures, crystallizes, and forms pellets. This boiler slag material is made up of hard, black, angular particles that have a smooth, glassy appearance. The particles are uniform in size, hard, and durable, with a resistance to surface wear.  | < 2.0%                        |

**Figures:**

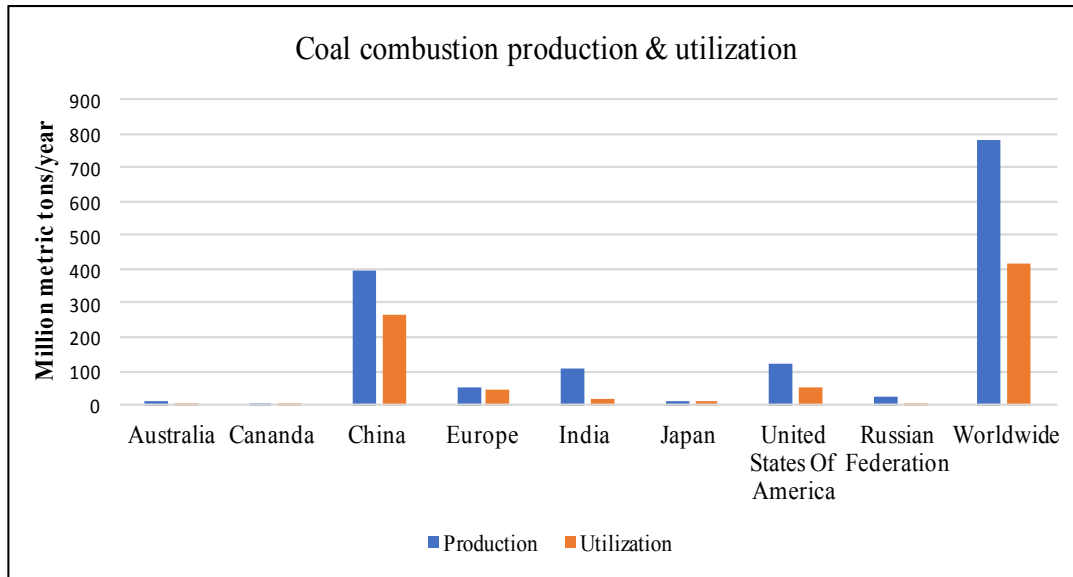


Figure 2.1 Coal combustion productions and utilizations [65]

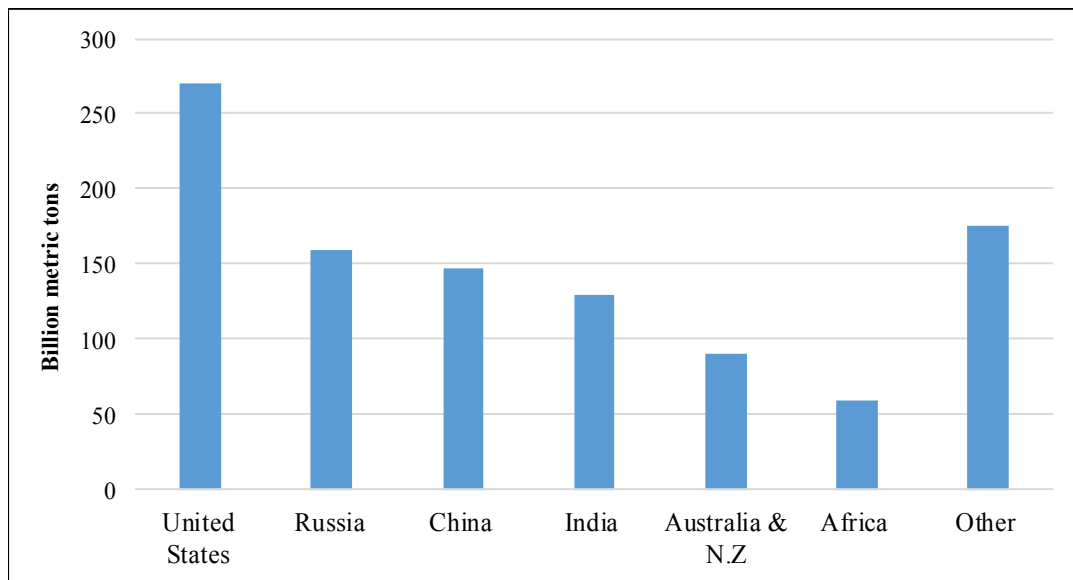


Figure 2.2 Coal reserves worldwide [65]



Figure 2.3 Coal – fired power plants in the United States [58]

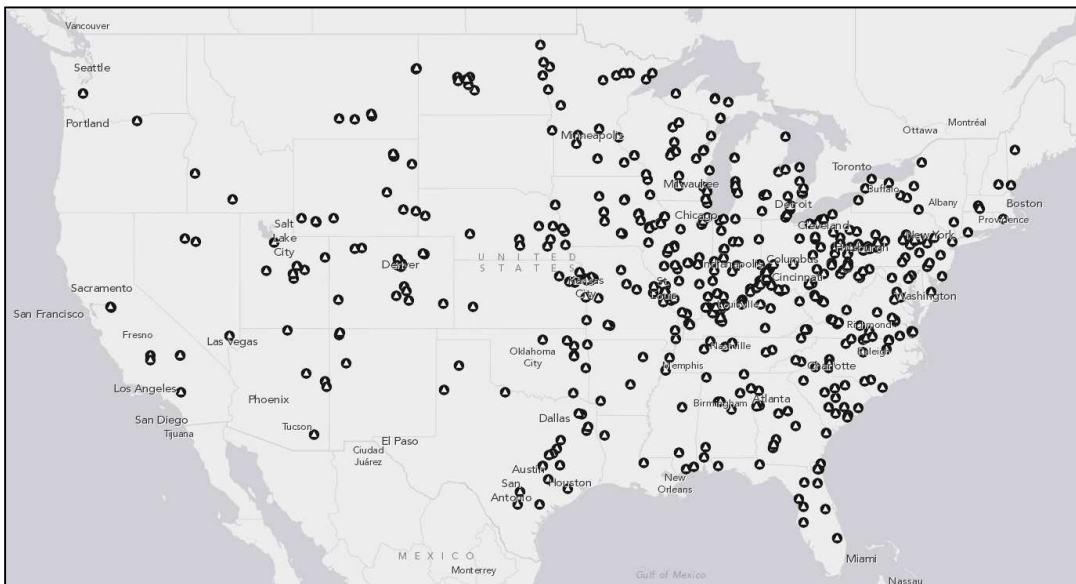


Figure 2.4 Map of coal plants in the United States [59]

CHAPTER 3  
MATERIALS AVAILABILITY AND ENERGY COSTS

In this section, we will see how the raw material sources including fly ash type F, silica fume, sodium hydroxide, coarse and fine aggregate, are used to produce the fly ash-based geopolymer concrete. My research shows that the materials used for fabrication of the fly ash-based geopolymer concrete (FGC) products include fly ash type F (ASTM C618) [64], silica fume, and sodium hydroxide will be introduced in this section. The activating solution (sodium hydroxide mixed with silica fume) preparation, casting and curing process will be explained in the next section.

### **3.1. Fly ash**

The major coal combustion products include about 85% fly ash, less than 15% bottom ash, and between 1-2% cenospheres. The annual coal combustion product production in the United States is around 118 million metric tons. Only 49.7 million metric tons are utilized, which is only 42.1% of produced materials [65]. Therefore, 51.9 % of fly ash is either dumped in the ground or stored outside. The stored fly ash has potential effects on the health of humans, animals, and plants. In addition, some of the stored underground fly ash may mingle with the groundwater, which may cause other negative effects. Therefore, it benefits everyone to make use of the coal combustion products. Due to high demand and production, high fly ash volume concrete is one of the potential solutions. In Table 3.1, it is clear that fly ash-based geopolymer concrete usually consists of 21% fly ash based geopolymer concrete weight. Figure 3.1 describes the fly ash production process.

Fly ash-based geopolymer concrete is a 100 percent fly ash replacement. It can be considered the fly ash utilization solution. It is recommended that fly ash-based geopolymer concrete industries are to be close to the fly ash sources because it will not only reduce the necessary cost for transportation, but it also reduces CO<sub>2</sub> due to transportation itself. On the East coast, the fly ash suppliers are distributed in North Carolina, Georgia, West Virginia, Massachusetts, Ohio, Tennessee, South Carolina, and Maryland [66]. All of them are producing Class F fly ash. Consequently, it is highly recommended to be the home of the fly ash concrete product industries. No process energy and non-energy emissions are attributed to the fly ash production because it is the byproduct of coal combustion for electrical power stations [67]. As a result, the process of fuel (thermal energy) usage and CO<sub>2</sub> emissions are assumed to be zero. The current cost of fly ash (Type F) is around \$35.0/ton, and it will be used throughout the research.

The producer price index (PPI) is shown in Figure 3.2 [84]. It demonstrates that fly ash price has decreased since 2012; however, the fly ash price gets higher by the end of 2015. The reason for this increase will be explained in the upcoming pages because the fly ash production in the United States has experienced shortages in recent years due to the federal government's regulations for reducing CO<sub>2</sub> emissions. However, based on the most recent interview with Dr. Adams Thomas, who is executive director of the American Coal Ash Association (ACAA), there are two reasons the future of fly ash is secure [76]. First, the price of natural gas will increase; hence, coal will be dispatched at a higher rate. The second reason is that most of the coal plants are well-equipped to meet government regulations; hence, fly ash production will increase again [76].

### 3.2. Sodium hydroxide

Sodium hydroxide (commonly known as caustic soda) is an inorganic material, which is white, solid, and highly caustic. It is produced in 50% (by mass) approximately saturated solution with water. The primary usage of sodium hydroxide is in pulp, paper, drinking water, soap, and drain cleaner. It was reported that the production of sodium hydroxide is around 60 million tons every year; however, the demand is around 51 million tons per year [77]. Physical properties are shown in Table 2.3. Sodium hydroxide is produced as white flakes, pellets, and as a solution. The reaction of sodium hydroxide with water is exothermic, and produces a large amount of heat [78].

Sodium hydroxide flakes are used to enhance the chemical reaction of fly ash. By looking at Table 3.1, mix 1, the maximum sodium hydroxide weight ratio to the binder including fly ash based silica fume concrete materials is 2.6%. The average compressive strength of this mix, when Wateree fly ash is used, is 106 MPa (15,400 psi) [9]. There are three methods to produce sodium hydroxide, including membrane cells, mercury cells, and diaphragm cells. Most of the United States production uses membrane and diaphragm cells. The most efficient method is membrane cells. Its energy efficiency is around 63% less than the theoretical minimum. Around three-quarters of the United States sodium hydroxide production comes by the diaphragm process. The rest comes mostly from the membrane method [67]. The United States' average production of sodium hydroxide is 11.2 million tons/year, while the total worldwide production is 44.0 million tons/year in 2004, (now the sodium hydroxide production is around 60.0 million tons/year). The database showed that the required energy (fuel usage or thermal energy)

for the production of sodium hydroxide is around 20.5 MJ/kg [69]. Figure 3.3 shows the sodium hydroxide production process.

Sodium hydroxide is usually produced in 50% concentration with water. The main method that is used for its production is the chloralkali process. The top worldwide producers are the United States, Europe, and Japan, respectively. The main producing companies in the United States are Dow Chemical Company in Texas and Louisiana, Oxychem, Pioneer Companies, and PPG [78]. The average current price of sodium hydroxide with 50% concentration is around \$580/ton in the United States, while in China it can be found for around (\$250-\$300)/ton with 25 tons as a minimum shipment. In this thesis, the price used in the calculation of geopolymers concrete cost is based on the price in the United States, which is considered the most expensive compared to other international producers. The producer price index (PPI) for sodium hydroxide is shown in Figure 3.4 [84]. It shows that the price of sodium hydroxide had a jump in 2009; however, it became steady after 2011. The reason attributed to the price jump is the economic crises in 2008.

### **3.3. Silica fume**

The American Concrete Institute (ACI) defines the silica fume by “very fine non-crystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon.” [79]. Silica fume is a byproduct which comes from the manufacture of ferrosilicon alloys or silicon. The collection procedure, which is used in the United States, is the dependent procedure. Silica fume, commonly known as microsilica, is an ultrafine byproduct. With an average particle diameter of 0.15  $\mu\text{m}$ -0.15  $\mu\text{m}$ . It is 100 times smaller than average Portland cement particles.



Therefore, it is a highly effective material due to the large surface area. The primary utilization of silica fume is in concrete. It can reduce durability, bleeding, and segregation of Portland cement concrete. Including silica fume in the Portland cement mixture improves the compressive and bonding strength as well as abrasion resistance [79]. Silica fume consists of 80-97% of silicon dioxide ( $\text{SiO}_2$ ), and less than 1% of calcium oxide ( $\text{CaO}$ ). Table 2.3 shows the physical properties of silica fume.

There are three other names of silica fume that are used in some scientific societies as follows:

- Condensed silica fume
- Microsilica
- Volatilized silica

The silica fume production is around 300,000 metric tons [80]. The main source of the silica fume comes from ferrosilicon. The silica fumes come as a byproduct due to capturing furnace off-gases. Ferrosilicon is generally used in the production of steel, as an alloying agent. The secondary production of silica fume is in the aluminum and chemical industries [80]. The Environmental Protection Agency (EPA) regulations have been enforced in the ferrosilicon industries requiring the collection of silica fume instead of pumping it in the air due to potential risks to living organisms. The production of these materials is expected to increase due to high demands of steel, iron, and alloys; hence, the silica fume productions will increase as well. The utilization of silica fumes in concrete applications has been encouraged for not only improving the quality of concrete properties but also for finding an appropriate application, which has high quantity demand.

Due to the fact that silica fume is a byproduct and cannot be produced without production of correlated products such as silicon in the case of silica fume, the silica fume's carbon dioxide emissions and the required production energy will not be considered in the calculations in this research. Therefore, the required energy will be zero. Figure 3.5 describes the silica fume production process. The current average price of silica fumes in the United States markets is around \$640/metric ton, while it is around \$182/metric ton in China. In this research, the price of silica fume was based on the United States price, which is \$640/metric ton.

**Tables:**

Table 3.1 Mixture proportions

| Concrete type                                | Fly ash (type F), kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Portland cement replacement, % | Water, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | w/b ratio | Sodium hydroxide, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Silica fume, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Compressive strength, MPa (psi)<br>SD |
|--|---|--------------------------------|--|-----------|---|--|---------------------------------------|
| Mix 1: silica fume based activating solution | 474 (29.6)  | 0.00                           | 163 (10.2)                                     | 0.28      | 61.6 (3.81)   | 46.2 (2.91)  | 106 (15,400)<br>4.96 (720)            |
| Mix 2: silica fume based activating solution | 474 (29.6)  | 0.00                           | 163 (10.2)                                     | 0.28      | 61.6 (3.81)   | 46.2 (2.91)  | 27.2 (3,940)<br>2.14 (310)            |
| Mix 3: Silica fume based activating solution | 450 (29.6)  | 5.00                           | 163 (10.2)                                     | 0.28      | 61.6 (3.81)   | 46.2 (2.91)  | 53.3 (7,730)<br>1.72 (250)            |
| Mix 4: silica fume based activating solution | 427 (29.6)  | 10.0                           | 163 (10.2)                                     | 0.28      | 61.6 (3.81)   | 46.2 (2.91)  | 57.4 (8,320)<br>2.07 (300)            |
| Mix 5: silica fume based activating solution | 403   | 15.0                           | 163 (10.2)                                     | 0.28      | 61.6 (3.81)   | 46.2 (2.91)  | 68.5 (9,930)<br>1.65 (240)            |

SD = Standards deviation for four samples

Table 3.2 Sodium hydroxide properties [78]

| Physical properties |                              |
|---------------------|------------------------------|
| Chemical formula    | NaOH                         |
| Molar mass          | 40.0 g mol <sup>-1</sup>     |
| Appearance          | White, waxy, opaque crystals |
| Density             | 2.13 g/cm <sup>3</sup>       |
| Melting point       | 318 °C (604 °F; 591 K)       |
| Boiling point       | 1,390 °C (2,530 °F; 1,661 K) |

Table 3.3 Physical properties of silica fume [79]

| Physical properties of silica fume |                                     |
|------------------------------------|-------------------------------------|
| Particle size (typical)            | < 1 μm                              |
| Bulk density<br>(as-produced)      | 130 to 430 kg/m <sup>3</sup>        |
| (densified)                        | 480 to 720 kg/m <sup>3</sup>        |
| Specific gravity                   | 2.2                                 |
| Specific surface                   | 15,000 to 30,000 m <sup>2</sup> /kg |

Figures:



Figure 3.1 Fly ash production process

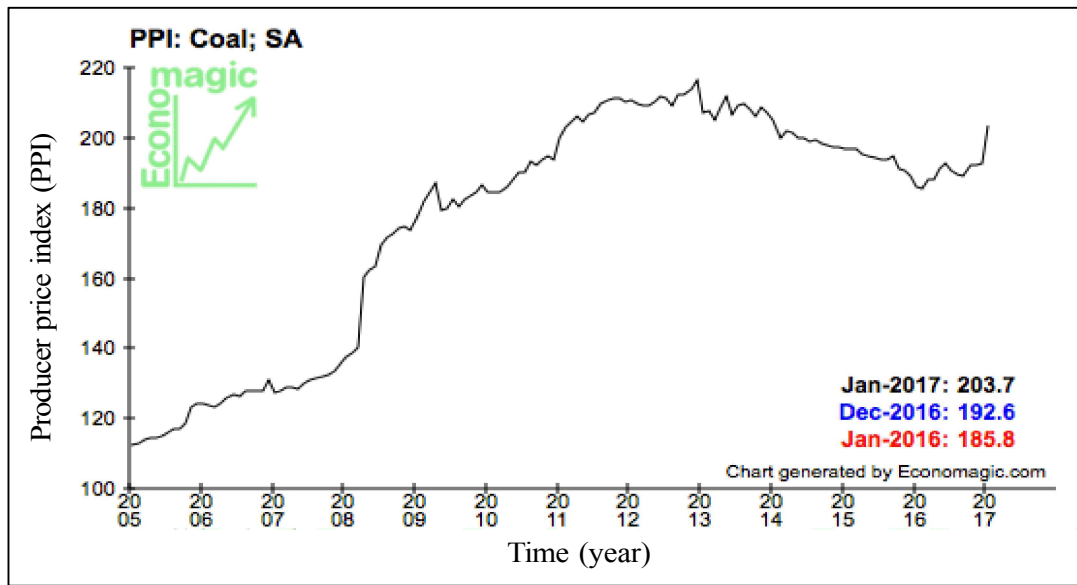


Figure 3.2 Fly ash producer price index (PPI) [84]



Figure 3.3 Sodium hydroxide production process

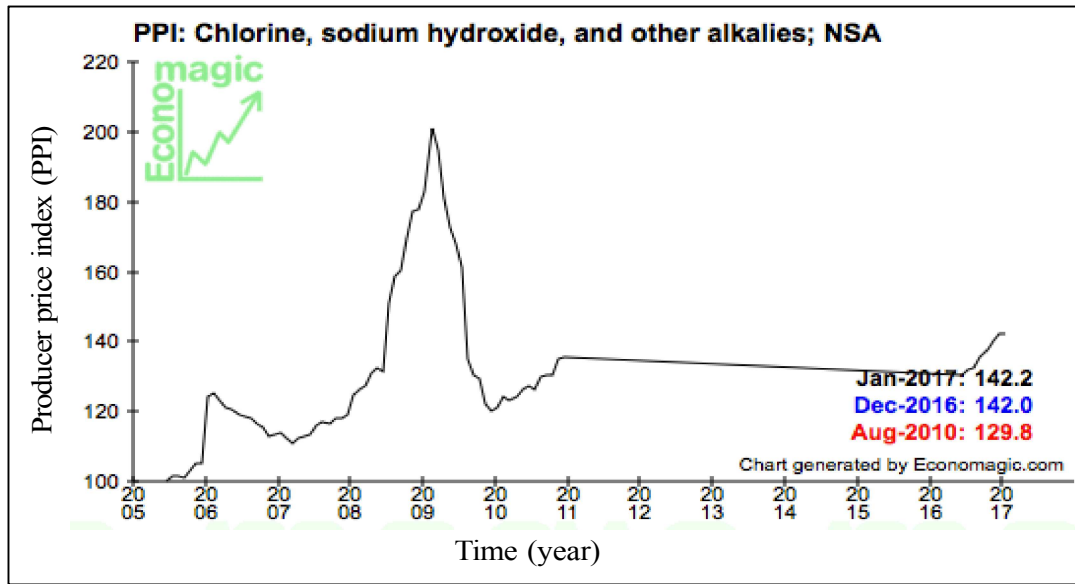


Figure 3.4 Sodium hydroxide producer price index (PPI) [84]



Figure 3.5 Silica fume production process

CHAPTER 4  
MATERIALS AND METHODS

In this section, the alternative activating solution which is a mixture of sodium hydroxide, silica fume, and water, will be the main focus. The required energy and cost will be calculated based on the available data in the United States of America. In addition, the cost and fuel (thermal energy) usage will be optimized and assessed based on some previous studies such as Assi, et al. [70], and some of the new mix designs will be introduced. Because the Portland and geopolymer concretes have approximately the same amount and type of coarse and fine aggregate, the coarse and fine aggregate cost and their associated thermal energy will not be considered.

A number of materials are required to produce one cubic meter ( $m^3$ ) of geopolymer or Portland cement concrete and, will be considered the base values in the comparison. The reference compression strength for geopolymer concrete for heated and unheated cured samples is 106 MPa (15,400 psi) and 64.3 MPa (9,330 psi), respectively [9, 70]. For the Portland cement, the compressive strength reference will be chosen according to the compressive strength of geopolymer concrete samples mentioned above. The assumed ambient condition in the lab will be 21.0 °C [69.8 °F].

#### **4.1. Activating solution**

Sodium hydroxide flakes were dissolved in water and stirred manually. The silica fume powder was then added and stirred for two minutes. The mixing of silica fume with sodium hydroxide and water resulted in an exothermic process (exceed 80.0 °C [176 °F]).



The activating solution was kept in an enclosed container in an oven at 75 °C (167 °F) for 12 hours to assure that the sodium hydroxide flakes and silica fume powder were completely dissolved. Providing a well-isolated container will reduce the required energy for keeping the temperature around 75 °C [176 °F], as well as reducing the corresponding CO<sub>2</sub> emissions. Due to the fact that the reaction of sodium hydroxide and water and the addition of silica fume is an exothermic reaction with more than 75 °C [176 °F], the required energy to elevate the activating solution from 21 °C [70 °F] to the 75 °C [176 °F] will be disregarded. The required amount of activating solution is around 100L,

Assuming the height equals double the diameter, its surface area is 1.25 m<sup>2</sup>. As a result, the required energy for maintaining the isolated tank under 75.0 °C [176 °F] for 24 hours in 21.0 °C [69.8 °F], with a height equals two times of diameter, is 5.80 MJ/100L [81].

#### **4.2. Casting and curing**

The dry ingredients (fly ash, fine aggregates, and coarse aggregates) were mixed for three minutes. The activating solution, which includes the water, was then added to the dry mixture and mixed for five minutes. For the silica fume based activating solution geopolymer cement, the specimens were left in ambient condition for two days and then heated for two days in an oven at 75.0 °C (167 °F) [17] in the case of heat cured samples. According to Tempest, et al., the required heat for raising the sample with one cubic meter size from 21.0°C [70 °F] to 75.0 °C [167 °F], is 103 MJ/m<sup>3</sup> [81]. By assuming the height of a well-isolated container equals twice of the diameter, the estimated heat losses

are 2.60 MJ/ h. Therefore, the required energy for maintaining the sample under 75.0 °C (167 °F) for 48 hours is 126 MJ/m<sup>3</sup>. Table 4.1 shows the required energy values.

Due to the similarity between the geopolymer and Portland cement mixing procedure, the required energy (labor and mixing machine) for mixing is disregarded for both case study.

**Tables:**

Table 4.1 The required energy for 100 and 106 MPa (Standard mix) compressive strength of Portland and geopolymer concrete

| Raw materials  | Amount, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Required energy, GJ |
|--|---|---------------------|
| Cement Type I,   | 475 (29.8)                                      | 2.35                |
| Silica fume  | 46.2 (2.91)                                     | 0.00                |
| Fly ash (type F)   | 474 (29.6)                                      | 0.00                |
| Sodium hydroxide   | 61.6 (3.81)                                     | 1.26                |
| Curing under<br>75.0°C for 48 hrs                        | ----  | 0.13                |
| Heat of activating<br>solution<br>(167°F)                | ----  | 0.05                |
| Heat the concrete to<br>75°C<br>(167°F)                  | ----  | 0.10                |
| Total required<br>energy,<br>Portland cement             | ----  | 2.35                |
| Total required<br>energy, Portland<br>cement, Geopolymer | ----  | 1.50                |

CHAPTER 5  
RESULTS AND DISCUSSION

The source of energy consumption which is required to produce geopolymer concrete will be due to sodium hydroxide production, the activating solution preparation, and external heat for curing if it is presented. The required energy for fly ash and silica fume as explained earlier will not be taken into consideration because they are byproduct materials. The required energy for transportation will be considered and evaluated in future work according to the available data of the product source and assumed geopolymer industry sites. The cost of geopolymer concrete will be calculated depending on the local price of raw materials. The material costs are most likely to vary with the offer and the request. The cost of transportations will vary as well due to the amount ordered and gas price variation. Therefore, the cost will be calculated depending on the average and most expected value.

Because the cost and amount of both the fine and coarse aggregates in geopolymer concrete and Portland concrete are the same, they will not be calculated into the cost of geopolymer and Portland cement concrete. CO<sub>2</sub> emissions of Portland and geopolymer concrete will be evaluated in future work. However; required energy (fuel usage) will give a reasonable indication of CO<sub>2</sub> emissions due to the geopolymer concrete production. The superplasticizer cost will be left out due to relatively low cost compared with other materials. The compared functional unit will be one m<sup>3</sup> of concrete with 106 MPa (15,400 psi) [9] in the case of using elevated heat, and 1 m<sup>3</sup> of 57.4 MPa (8,320 psi), 68.5 MPa (9,930 psi) for 10% and 15% Portland cement replacement [70].

The cost and fuel (thermal energy) usage of the required paste to make one m<sup>3</sup> of geopolymers or Portland cement concrete will be calculated and compared in this section.

### **5.1. Calculation of energy requirements and predicted cost for the standard mix and corresponding Portland cement compressive strength**

In this section, the energy requirements are calculated. The compressive strength will be based on the experimental results of Assi, et al. [9]. The seven-day compressive strength as shown in Table 3.1 is 106 MPa (15,400 psi) in the presence of external heat for two days. The 90% compressive strength was achieved in less than seven days. Accordingly, a similar compressive strength is chosen for Portland cement concrete based on the Portland Cement Association (PCA) book [71]. The mix design is shown in Table 5.1. The CO<sub>2</sub> emissions, fuel usage requirements for transportation, fuel usage for fly ash, and fuel usage for silica fume were considered. The coarse and fine aggregate cost and energy canceled due to the similarities between geopolymers and Portland cement concrete.

As shown in Table 5.2, the required amount of Portland cement to make one m<sup>3</sup> is 475 kg. The necessary energy for producing 475 kg of Portland cement with 100 MPa (14,500 psi) compressive strength, calculated according to the Energy Consumption Benchmark Guide: Cement Clinker Production [72], was 2.35/m<sup>3</sup> GJ. On the other hand, according to the standard mix in Table 3.1, the energy consumption required for producing one m<sup>3</sup> of geopolymer concrete with 106 MPa (15,400 psi) was around 1.5 GJ/m<sup>3</sup>. The necessary fuel energy for producing geopolymer concrete is 36 % less than for Portland concrete. In addition, the results show that sodium hydroxide is responsible for 80 % of the total fuel usage. The fuel usage reduction in the geopolymer concrete is a

preferred sign from the CO<sub>2</sub> emissions standpoint when geopolymer concrete is compared with Portland cement. Figure 5.1 shows the comparison between geopolymer and Portland cement from the fuel (thermal energy) usage standpoint.

On the other hand, the costs of silica-based activating geopolymer and Portland cement were calculated based on the current price of raw materials. The costs may fluctuate depending on the demanded and provided amounts in the marketplace. Because the amount and type of aggregates are the same for both geopolymer and Portland cement concrete, the cost will be left. In addition, the labor costs will be eliminated due to the slightly smaller difference between geopolymer and Portland cement concrete, and they have little effect on the final cost. The estimated current price of raw materials is shown in Table 5.3. As shown in the equations below, the estimated standard mix cost of geopolymer concrete was \$118, while the estimated cost of Portland cement was \$98.1. The difference in the cost is 17%. As shown in Figure 5.1 and 5.2, the sodium hydroxide cost and fuel usage play dominant roles in the cost and fuel energy of geopolymer concrete.

Geopolymer concrete helps in reduction of required energy by 36% in comparison with Portland cement. The fuel (thermal energy) usage will reflect on the CO<sub>2</sub> emissions reduction. Furthermore, geopolymer concrete utilizes waste materials such as fly ash and slag. All of the desired properties make geopolymer concrete more desirable than other concrete types from an environmental standpoint even though it is costly. The performance of geopolymer concrete against sulfate attack, fire resistance, and harsh weather conditions is superior in comparison with Portland cement concrete. These facts may help to offset the high-cost concerns.

The following equations are for calculating the cost of geopolymer and Portland cement:

$$\text{Cost of Portland} = \text{wt. PC} \cdot \text{cost PC} + \text{wt. of SF} \cdot \text{cost SF} \dots\dots\dots 1$$

$$\text{Cost of Portland} = 0.475 \cdot 105.5 + 0.075 \cdot 640 = \$ 98.11 / \text{ton}$$

$$\text{Cost of geopolymer} = \text{wt. fly ash} \cdot \text{cost FA} + \text{wt. SH} \cdot 2 \cdot (50\%) \cdot \text{cost SH} + \text{wt. SF} \cdot \text{cost SF} \dots\dots\dots 2$$

$$\text{Cost of geopolymer} = 0.474 \cdot 35 + 0.0616 \cdot 2 \cdot 580 + 0.0462 \cdot 640 = \$ 117.6 / \text{ton}$$

Where,

- wt. = weight of
- FA = fly ash
- SF = silica fume
- SH = sodium hydroxide
- PC = Portland cement

## 5.2. Optimization of the cost and fuel usage of geopolymer concrete

In this section, optimizing the cost and fuel energy of geopolymer concrete will be the main focus. Based on the previous section, the cost of sodium hydroxide and fuel usage has the main determining factor of the total cost of geopolymer concrete. In addition, the major fuel usage of geopolymer concrete comes from sodium hydroxide. The dominant factors on the cost and energy requirements will be based on the experimental results published recently by Assi et al. in 2016 [70] due to the similarities in the activating solution which is a mixture of silica fume, sodium hydroxide, and water. The effect of eliminating the practical barriers, such as external heat, on the cost, thermal energy usage, and customer needs will be examined. As shown in Figures 5.1 and 5.2, sodium hydroxide plays a dominant part in the fuel usage and cost as well. For instance, the sodium hydroxide is responsible for 83 % of the required energy, and 61% of the cost of production of geopolymer cement. Therefore, the attention will be on reducing the



sodium hydroxide concentration while keeping the same or an acceptable level of performance from an engineering standpoint.

In addition, external heat has a lower effect on the cost and thermal energy usage of geopolymer cement, in comparison with sodium hydroxide. For example, the fuel energy effect is 8.6 % of the total fuel energy of geopolymer cement. However, the absence of external heat is essential from an engineering applications standpoint. Geopolymer cement, which needs external heat to be cured, cannot be used in civil engineering applications such as sidewalks, highways, and dam masonry. Therefore, in these applications eliminating external heat is significant.

#### **5.2.1. Effect of sodium hydroxide concentration on cost and fuel usage**

In Assi et al. [70]'s experimental work, sodium hydroxide concentration was reduced by 25, 50 and 75 % respectively in comparison with the mixture proportion in Table 3.1, in the presence of external heat. The compressive strength, as shown in Table 5.4, was 106 MPa (15,3800 psi), 54.5 MPa (7900 psi), 11.7 MPa (1,700 psi), and 0 for 0, 25, 50 and 75% sodium hydroxide reduction. The cost and thermal fuel energy usage are shown in Figure 5.3 and 5.4. By considering the zero-sodium hydroxide reduction as a reference, the cost was reduced by 16%, 33% and 47% when sodium hydroxide was reduced by 25%, 50%, and 75%.

Additionally, the energy usage was reduced by 20%, 40%, and 60% when sodium hydroxide was reduced by 25%, 50%, and 75% respectively. Table 5.4 shows the estimated cost and fuel usage for the sodium hydroxide concentration reductions. The results prove that sodium hydroxide should be the main target to reduce the price and fuel usage; however, the compressive strength will be decreased drastically as shown in Table

5.4. The partial Portland cement replacement may solve this problem due to the extra calcium hydroxide which will be presented when the hydration process takes place as explained by the literature [70].

### **5.2.2. Effect of external heat on the cost and thermal energy**

In this section, the effect of external heat on the cost and fuel (thermal energy) usage will be investigated. As shown in Table 5.5 and Figure 5.5, the cost was not affected due to eliminating the external heat cost. The percentage of external heat to the total fuel usage is 8.4%. As shown in Figure 5.6, the effect of external heat on the curing process seems low. When the external heat is eliminated, the total energy usage was 8.5% less in comparison with the case of external heat. Therefore, the effect of external heat plays a low role in cost and fuel usage.

However, in several engineering applications, eliminating the use of external heat plays a critical role in an engineer's decision to use the geopolymer concrete. For example, external heat cannot be provided for some engineering applications such as sidewalks, shoulders, and highway construction. In the presence of external heat, geopolymer usage will be dedicated to precast and prestressed applications including bridge decks, wall panels, and girders.

### **5.2.3. Effect of Portland cement replacement on the cost and fuel thermal energy**

In this section, the effect of Portland cement replacement on the fuel (thermal energy) usage, cost, and compressive strength of geopolymer concrete is investigated. A comparison is made between geopolymer concrete and Portland cement concrete based on the corresponding compressive strength. The experimental results are lent from a previous experimental work conducted by Assi, et al. [70]. In this research, four different Portland cement replacements were investigated including 0, 5, 10 and 15%. The geopolymer concrete samples were cured at an ambient condition. The compressive strength was measured at 1, 3, 7, and 28 days. In this current work, the cost and fuel usage for 28-day compressive strength will be calculated. The mixing proportions and compressive strength are shown in Table 3.1 and Table 5.6 respectively. The absence of the external heat usually reduces the compressive strength; however, replacing fly ash with Portland cement partially improves the compressive strength and other properties such as absorption and microstructure.

Due to the absence of the external heat for the curing process, the fuel usage required for raising the concrete samples from ambient condition to the oven temperature and for maintaining the concrete samples in the oven temperature for 48 hours was eliminated. The fuel (thermal energy) usage for the geopolymer concrete is shown in Figure 5.7. The fuel usage was increased from 1.31 to 1.68 GJ/m<sup>3</sup> when Portland cement replacement increased from 0 to 15 %. However, the maximum of the total fuel usage of 15% Portland cement replacement is lower than Portland cement by 28.5%. Table 5.6 summarizes the calculated fuel usage, cost, and compressive strength of geopolymer

concrete at 28 days. By comparing the 15% Portland cement replacement, the Portland cement is 29% higher than 15 % Portland cement replacement.

The cost of geopolymer concrete increased when Portland cement replacement was used instead of fly ash. As shown in Figure 5.8, the cost was \$118, \$120, \$123, and \$125 per cubic meter. The percent difference between 0 and 15% was 6 percent. However, the compressive strength improvement was 57.7% in comparison with the zero Portland cement replacement. Therefore, for each dollar increase in the cost, the compressive strength increases by 5.0 MPa in the case of using Portland cement as a replacement in the geopolymer concrete. The need for external heat for curing is not required.

In conclusion, the effect of using Portland cement as the replacement has little effect on the fuel usage and cost of geopolymer concrete. However, it eliminates using external heat, and also improves the compressive strength. The effect of using Portland cement replacement on the total fuel usage and cost of geopolymer concrete was minimal; while the effect of sodium hydroxide and silica fume on the cost and fuel usage was high. Therefore, a combination of reducing sodium hydroxide concentration, and increasing Portland cement replacement on the mechanical, and microstructural properties, as well as cost, CO<sub>2</sub> emissions, and fuel (thermal energy) usage, will be investigated.

#### **5.2.4. Calculation energy requirements and predicted cost for mix 5 and corresponding Portland cement compressive strength**

A simple comparison between the mix 5 in Table 3.1 of geopolymer concrete, which has a compressive strength of around 68.5 MPa (9,930 psi), with a corresponding

Portland cement compressive strength, which is 70 MPa, is shown in Table 5.7. The mix design shown in Table 5.7 was based on information the Portland Cement Association (PCA) book [71]. As shown in Table 5.7, Table 5.8, and Figure 5.9, the fuel (thermal energy) usage of one cubic meter for the geopolymer concrete with 15% Portland cement is 1.66 GJ, while for the Portland cement concrete it is 2.20 GJ. The difference in fuel (thermal energy) usage is 33% less for 15% Portland cement replacement geopolymer concrete in comparison with the conventional concrete.

Figure 5.10 shows the cost of the 15% Portland cement replacement geopolymer paste, which is required to make one cubic meter of concrete, and the amount of Portland cement paste required to make one cubic meter of concrete. The cost of geopolymer concrete with 15% replaced Portland cement concrete is 34% higher than Portland cement concrete. The cost difference may discourage from using customers to use the geopolymer concrete; however, by reducing the sodium hydroxide concentration and silica fume will help to reduce the total cost of geopolymer concrete because the cost of sodium hydroxide is about 80% of the total of the geopolymer cost.

#### **5.2.5. Calculation of energy requirements and predicted cost for mix 6-8 and corresponding Portland cement compressive strength**

Based on the findings from the previous section, sodium hydroxide and silica fume have the dominant role in the cost of geopolymer concrete; and the external heat may limit geopolymer concrete applications. The sodium hydroxide concentration not only has an impact on the cost, but also on the fuel usage. It consists of 96% of the total required fuel usage. In addition, partial Portland cement replacement was found to have neither a significant impact on the cost nor on the fuel usage.

Those same findings show conclusively that sodium hydroxide and silica fume have the dominant role in the cost of geopolymer concrete; and the external heat may limit geopolymer concrete applications. The sodium hydroxide concentration not only has an impact on the cost, but also on the fuel usage. It consists of 96% of the total of the required fuel usage. In addition, the partial Portland cement replacement was found neither to have a significant impact on the cost nor the fuel usage.

In this section, three new geopolymer mixes are proposed to reduce the cost and fuel usage, in the absence of external heat for curing requirements. As shown in Table 5.9, the controlled mix was considered to have 100% sodium hydroxide and 100% silica fume concentration in comparison with the new mixes. Mixes 6, 7, and 8 have 75%, 75%, 50%, 50%, and 25%, 25% of sodium hydroxide and silica fume weight ratio respectively in comparison with the controlled mixture. Portland cement was used as weight replacement in place of fly ash. Based on the findings in Assi et al [70], Portland cement enhances the geopolymerization process because it contributes an additional caustic, which is calcium hydroxide, and reduces the free water. Therefore, in these mixes, as sodium hydroxide concentrations were decreased Portland cement replacement was increased by 15%, 25%, 35% for mix 6, 7, and 8, respectively. Table 5.10 shows the 28-day compressive strength in the absence of external heat, cost, and fuel usage results.

The cost was \$118, \$97.5, \$75.6, and \$53.6 for the controlled mix, mix 6, 7, and 8 respectively. By considering the controlled mix as a reference for cost and fuel usage, the cost reduction was 17%, 35%, and 55% for mix 6, 7, and 8 respectively. The fuel usage was 1.37 GJ/m<sup>3</sup>, 1.29 GJ/m<sup>3</sup>, 1.22 GJ/m<sup>3</sup> for mix 6, 7, and 8 respectively, while it was 1.31 GJ/m<sup>3</sup> for the controlled mix. The cost and fuel usage are shown in Figure 5.11 and

Figure 5.12, respectively. As shown in Figure 5.11, fuel usage has a slight reduction in comparison with the controlled mix; however, it is lower than the corresponding Portland cement mixes by at least 50%. The corresponding Portland cement mixes were chosen based on the compressive strength [82, 83]. Table 5.11 shows the two chosen Portland cement mixes, in which mix-9 has zero fly ash, while mix-10 has 15% fly ash and 7.5% silica fume. As shown in Figure 5.13, the 28-day compressive strength was 27.0 MPa (3,920 psi), 29.2 MPa (3,920 psi), 29.1 MPa (3,920 psi), 15.2 MPa (2,180 psi) for the controlled mix, and mix 6, 7, and 8, respectively. It seems that mix 6 and 7 are promising because they have a competitive cost as well as lower fuel usage in comparison with the Portland cement mix cost and fuel usage.

The new proposed mixes, in the absence of external heat, reduced the cost of geopolymer concrete by 55%; however, some Portland cement mixes have a lower cost. The geopolymer concrete has a unique advantage, which is 90% of the final compressive strength can be achieved within 24 hours. The durability, fire resistance, and performance may also be improved in comparison with Portland cement. Such advantages may potentially be considered worth the extra cost.

**Tables:**

Table 5.1 Mix design for 100 MPa compressive strength of Portland cement concrete [71]

| Raw materials  | kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) |
|--|---|
| Cement Type I  | 475 (29.8)                              |
| Silica fume  | 74.1 (4.65)                             |
| Fly ash (type F)                                     | 104 (6.53)                              |
| Coarse aggregate SSD (12.5 mm crushed limestone), kg | 1,070 (67.2)                            |
| Fine aggregate SSD, kg                               | 593 (37.2)                              |
| HRWR Type F, liters                                  | 16.4 (4.33)                             |
| Retarder, Type D, liters                             | 1.50 (0.40)                             |
| w/c  | 0.23                                    |

Table 5.2 Required energy for 100 and 106 MPa compressive strength of Portland and geopolymer concrete (Standard mix)

| Raw materials  | Amount, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Required energy, GJ |
|--|---|---------------------|
| Cement Type I  | 475 (29.8)                                      | 2.35                |
| Silica fume  | 46.2 (2.90)                                     | 0.00                |
| Fly ash (type F)   | 474 (29.6)                                      | 0.00                |
| Sodium hydroxide   | 61.6 (3.80)                                     | 1.26                |
| Curing under 75.0 °C (167 °F) for 48 hrs                 | ----  | 0.13                |
| Heat of activating to 75.0 °C (167 °F) solution (167 °F) | ----  | 0.05                |
| Heat the concrete to 75.0 °C (167 °F)                    | ----  | 0.10                |
| Total required energy, Portland cement                   | ----  | 2.35                |
| Total required energy, Portland cement, Geopolymer       | ----  | 1.50                |



Table 5.3 Raw materials price

| Raw materials          | \$/metric ton |
|------------------------|---------------|
| Cement Type I,         | 106           |
| Silica fume            | 640           |
| Fly ash (type F)       | 35.0          |
| Sodium hydroxide (50%) | 580           |

Table 5.4 Seven-day compressive strength, cost and fuel usage of geopolymer concrete due to changing sodium hydroxide concentration

| Sodium hydroxide concentration reduction, % | Compressive strength MPa, (psi) | Standard deviation (SD) MPa (psi) | Cost, \$ | Fuel (thermal energy) usage, GJ |
|---|---------------------------------|-----------------------------------|----------|---------------------------------|
| 0   | 106 (15,400)                    | 4.96 (720)                        | 117      | 1.51                            |
| 25  | 54.5 (7,910)                    | 1.52 (220)                        | 98.1     | 1.22                            |
| 50  | 11.7 (1,780)                    | 0.27 (40)                         | 80.3     | 0.91                            |
| 75  | 0.00                            | 0.00                              | 63.2     | 0.63                            |

Table 5.5 Seven-day compressive strength, cost and fuel usage of geopolymer concrete due to changing the external heat

| External heat, °C (°F) | Compressive strength MPa, (psi) | Standard deviation (SD) MPa (psi) | Cost, \$ | Fuel (thermal energy) usage, GJ |
|------------------------|---------------------------------|-----------------------------------|----------|---------------------------------|
| 25 (67.0)              | 30.3 (4,400)                    | 2.55 (370)                        | 117      | 1.45                            |
| 35 (95.0)              | 33.1 (4,800)                    | 3.72 (540)                        | 117      | 1.47                            |
| 45 (113)               | 68.5 (9,930)                    | 1.17 (170)                        | 117      | 1.49                            |
| 75 (167)               | 101 (14,700)                    | 4.96 (720)                        | 117      | 1.54                            |

Table 5.6 Seven-day compressive strength, cost, and fuel usage of partially replaced geopolymer concrete

| Fly ash (type F) weight replacement, % | Portland cement weight replacement, % | Compressive strength MPa, (psi) | Standard deviation (SD) MPa (psi) | Cost, \$ | Fuel (thermal energy) usage, GJ |
|--|---------------------------------------|---------------------------------|-----------------------------------|----------|---------------------------------|
| 0                                      | 0                                     | 27.2 (3,940)                    | 2.14 (310)                        | 118      | 1.31                            |
| 5                                      | 5                                     | 53.3 (7,730)                    | 1.72 (250)                        | 120      | 1.42                            |
| 10                                     | 10                                    | 57.4 (8,320)                    | 2.07 (300)                        | 123      | 1.61                            |
| 15                                     | 15                                    | 64.3 (9,330)                    | 1.65 (240)                        | 125      | 1.70                            |

Table 5.7 The required energy for 70 MPa compressive strength of Portland

| Raw materials                 | Amount, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Required energy, GJ |
|-------------------------------|---|---------------------|
| Cement Type I                 | 445 (29.8)                                      | 2.23                |
| Silica fume (Portland cement) | 56 (3.50)                                       | 0                   |
| Water                         | 474 (29.6)                                      | 0                   |
| Coarse aggregate              | 1,110 (69.4)                                    | ---                 |
| Fine aggregate                | 611 (38.2)                                      | ---                 |
| Total required energy         |   | 2.23                |

Table 5.8 Required energy for 69 MPa compressive strength of geopolymer concrete

| Raw materials                        | Amount, kg /m <sup>3</sup> (lb/ft <sup>3</sup> ) | Required energy, GJ |
|--------------------------------------|--|---------------------|
| Portland cement                      | 71.1 (4.6)                                       | 0.35                |
| Silica fume (geopolymer)             | 46.2 (2.91)                                      | 0.00                |
| Fly ash (type F)                     | 474 (29.6)                                       | 0.00                |
| Sodium hydroxide                     | 61.6 (3.80)                                      | 1.26                |
| Curing under 75 °C for 48 hrs        | ----   | 0                   |
| Heat of activating solution (167 °F) | ----   | 0.05                |
| Heat the concrete to 75 °C (167°F)   | ----   | 0                   |
| Total required energy,               | ----   | 1.66                |

Table 5.9 Mixture proportions for mix 6-8

| Concrete type                  | Fly ash F <sub>3</sub> , kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Water, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | w/c % | Sodium hydroxide, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Silica fume, kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Coarse agg., kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | Fine agg., kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) | SP % of fly ash | Cement Portland (kg/m <sup>3</sup> ) |
|--------------------------------|--|--|-------|---|--|--|--|-----------------|--------------------------------------|
| Controlled mix OPC-100SH-100SF | 474 (29.6)   | 163 (10.2)                                     | 28.0  | 61.6 (3.81)   | 46.2 (2.92)  | 793 (49.5)   | 793 (49.5)   | 1.50            | 0                                    |
| Mix-6 15%PC-75%SH-75%SF        | 403 (29.6)   | 155 (9.71)                                     | 26.6  | 46.2 (2.85)   | 34.6 (2.19)  | 793 (49.5)   | 793 (49.5)   | 1.50            | 71 15%                               |
| Mix-7 25%PC-50%SH-50%SF        | 356 (29.6)   | 155 (9.71)                                     | 26.6  | 30.8 (1.91)   | 23.1 (1.46)  | 793 (49.5)   | 793 (49.5)   | 1.50            | 119 25%                              |
| Mix-8 35%PC-25%SH-25%SF        | 308 (29.6)   | 155 (9.71)                                     | 26.6  | 15.4 (0.95)   | 11.6 (0.73)  | 793 (49.5)   | 793 (49.5)   | 1.50            | 166 35%                              |

SD = Standard deviation

Table 5.10 Results of 28-day compressive strength, cost, and fuel usage for the new mixes

| Concrete type                             | Average compressive strength, MPa (psi) | Standard deviation (SD) MPa (psi) | Fuel energy (GJ/m <sup>3</sup> ) | Cost (\$/m <sup>3</sup> ) |
|---|---|-----------------------------------|----------------------------------|---------------------------|
| Controlled mix<br>0PC-<br>100SH-<br>100SF | 27.2<br>(3,940)                         | 2.14<br>(310)                     | 1.31                             | 118                       |
| Mix-6<br>15%PC-<br>75%SH-<br>75%SF        | 29.2<br>(4,230)                         | 1.95<br>(283)                     | 1.37                             | 97.5                      |
| Mix-7<br>25%PC-<br>50%SH-<br>50%SF        | 29.2<br>(4,240)                         | 7.24<br>(1050)                    | 1.29                             | 75.6                      |
| Mix-8<br>35%PC-<br>25%SH-<br>25%SF        | 15.6<br>(2,270)                         | 0.16<br>(24.3)                    | 1.22                             | 53.6                      |

Table 5.11 Corresponding Portland cement mixture proportions

| Materials                           | Mix-9 :100PC-OFA-0SF<br>kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) [1] | Mix-10: 100PC-15FA-7SF<br>kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) [2] |
|-------------------------------------|---|---|
| Portland cement I                   | 335 (20.9)  | 392 (24.5)  |
| Fly ash (type F)                    | 0.00  | 80.1 (5.01)   |
| Silica fume                         | 0.00  | 38.6 (2.41)   |
| Compressive strength<br>MPa (psi)   | 35.1 (5,070)  | 33.2 (4820)   |
| Fuel energy<br>(GJ/m <sup>3</sup> ) | 1.65  | 1.93  |

**Figures:**

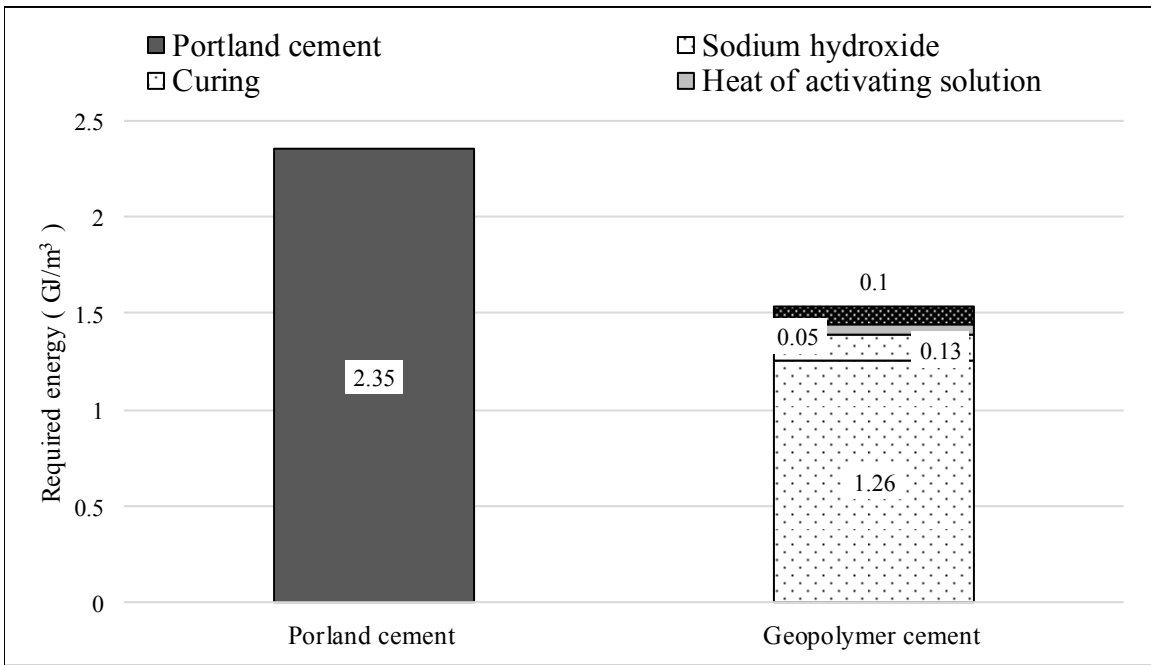


Figure 5.1 Fuel (Thermal energy) usage

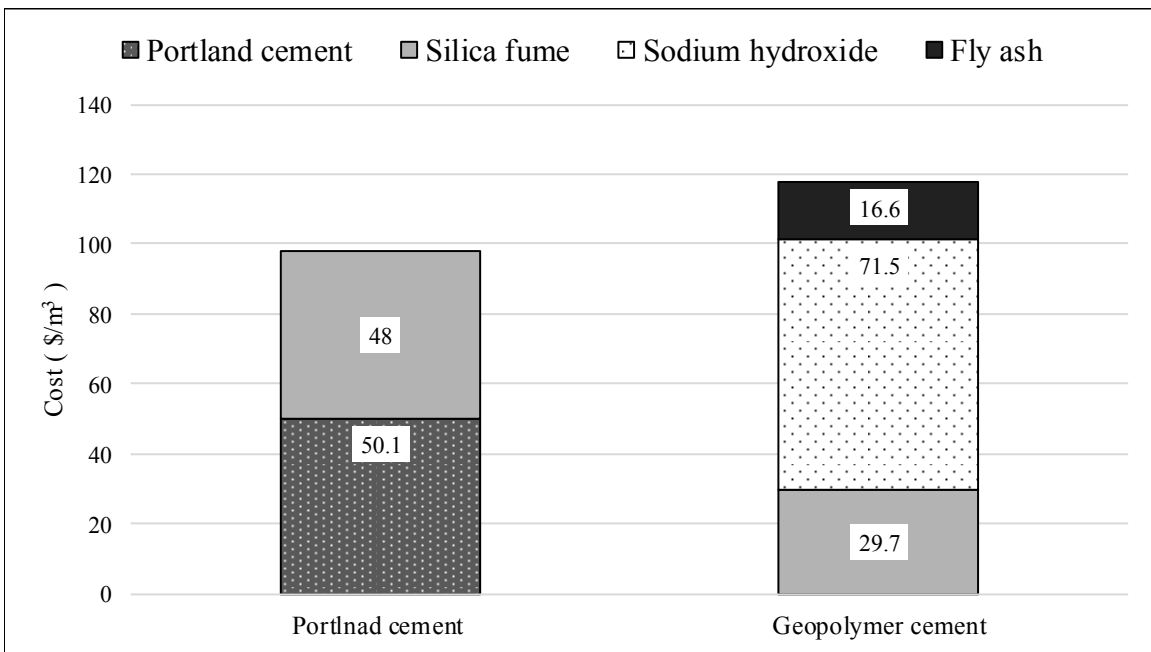


Figure 5.2 Cost of geopolymer and Portland cement concrete

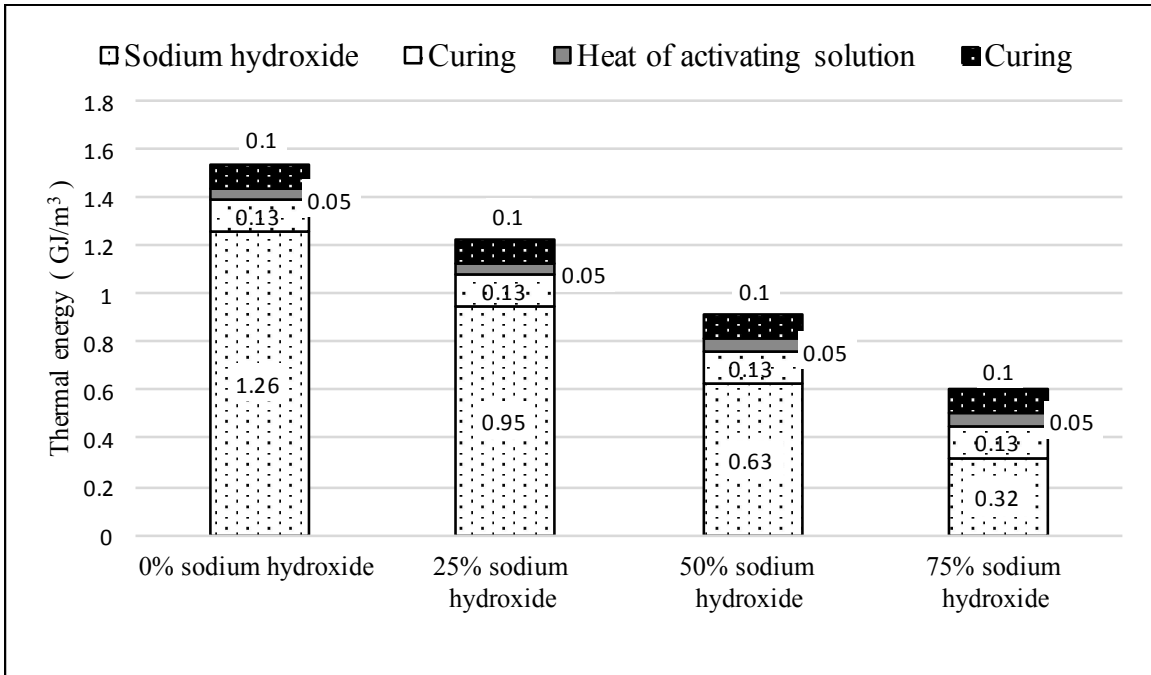


Figure 5.3 Optimizing fuel (Thermal energy) usage by sodium hydroxide concentration

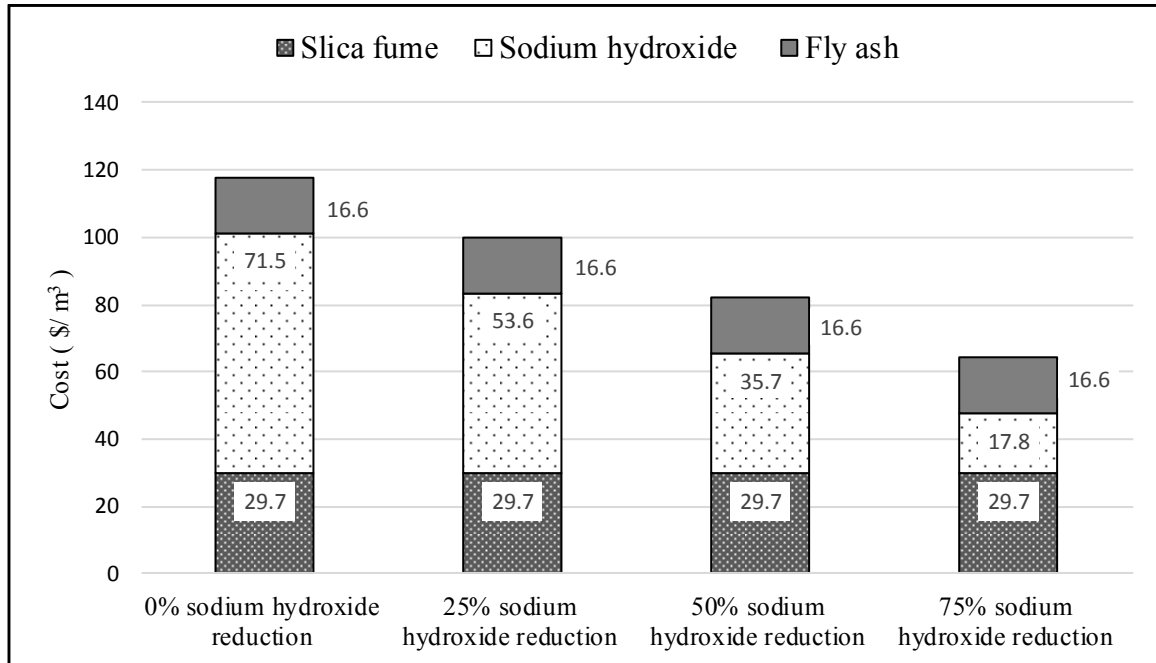


Figure 5.4 Optimizing cost of geopolymer by sodium hydroxide concentration

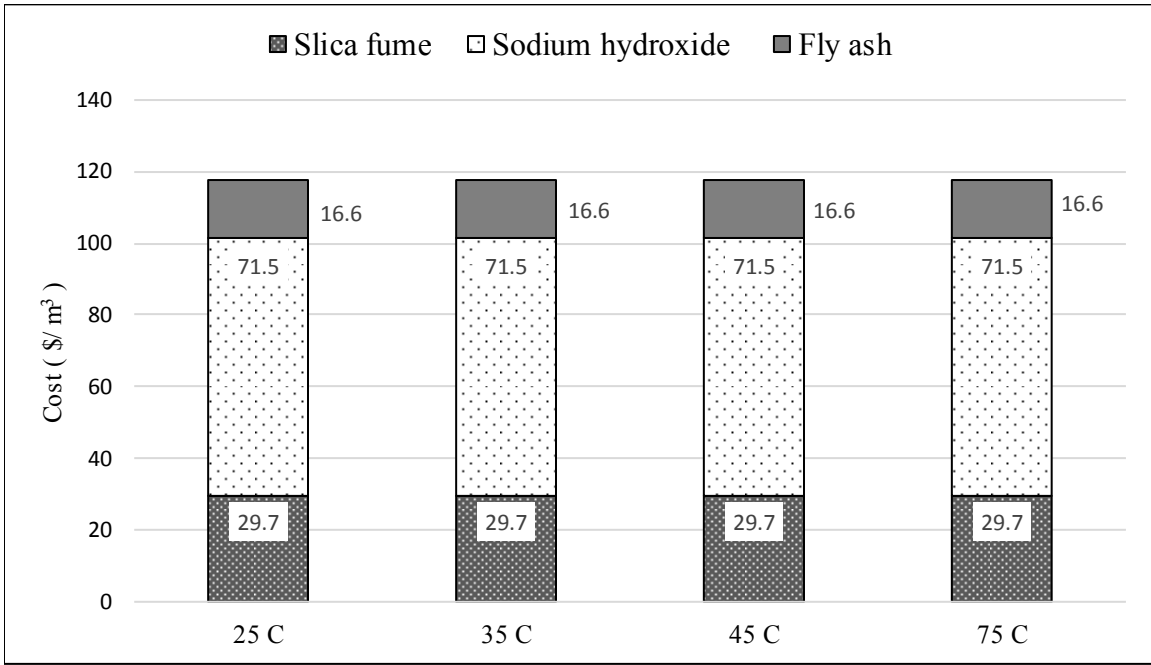


Figure 5.5 Optimizing the cost of geopolymer changing by external heat

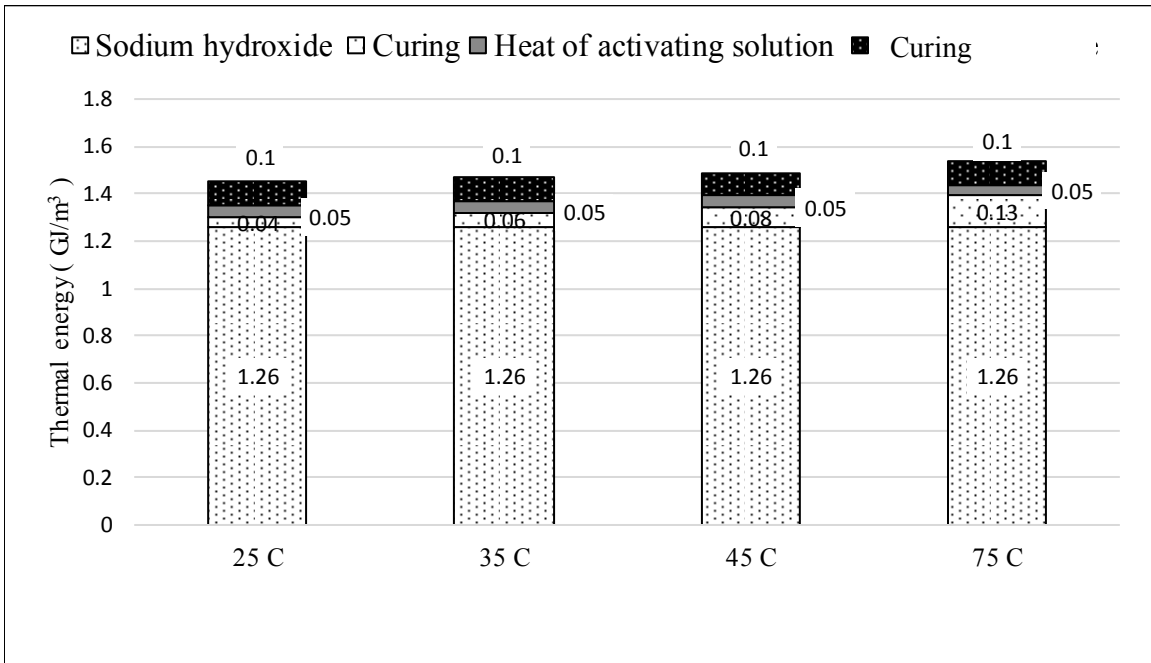


Figure 5.6 Optimizing thermal energy of geopolymer by changing external heat

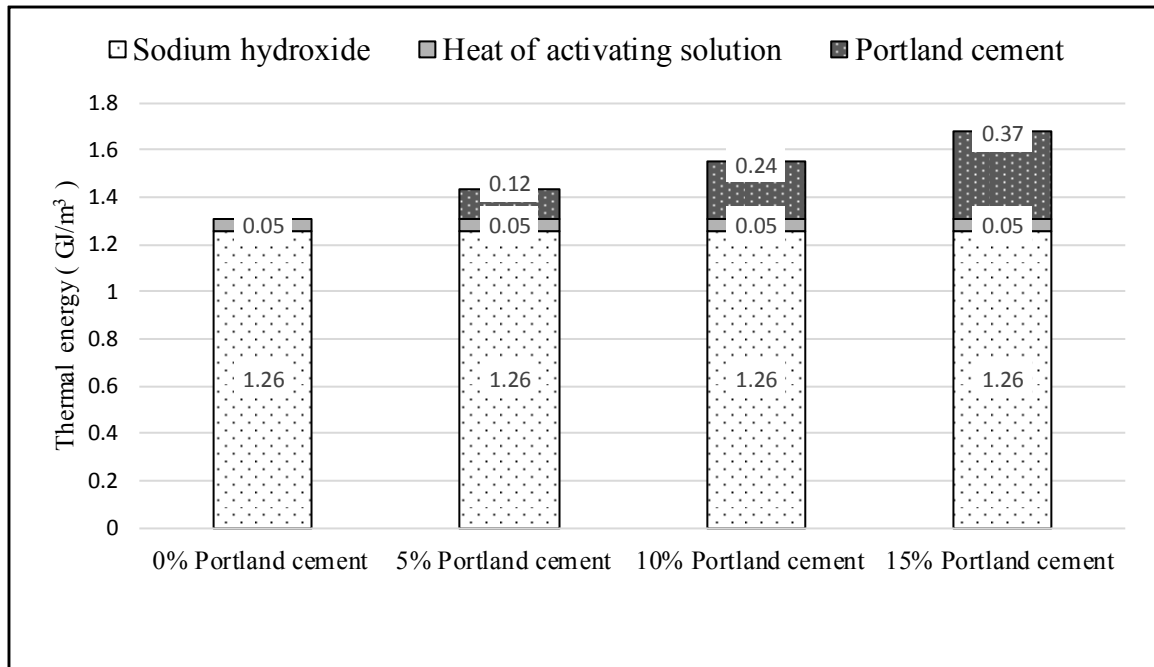


Figure 5.7 Effect of Portland cement replacement on fuel usage of geopolymer concrete

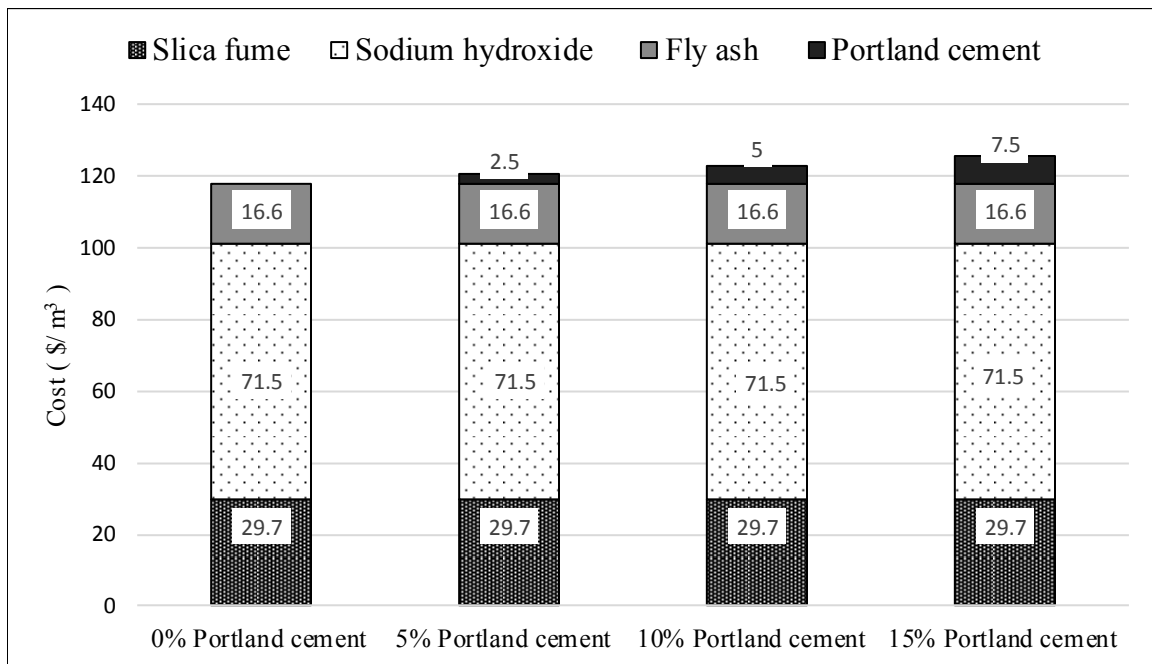


Figure 5.8 Effect of Portland cement replacement on cost of geopolymer concrete



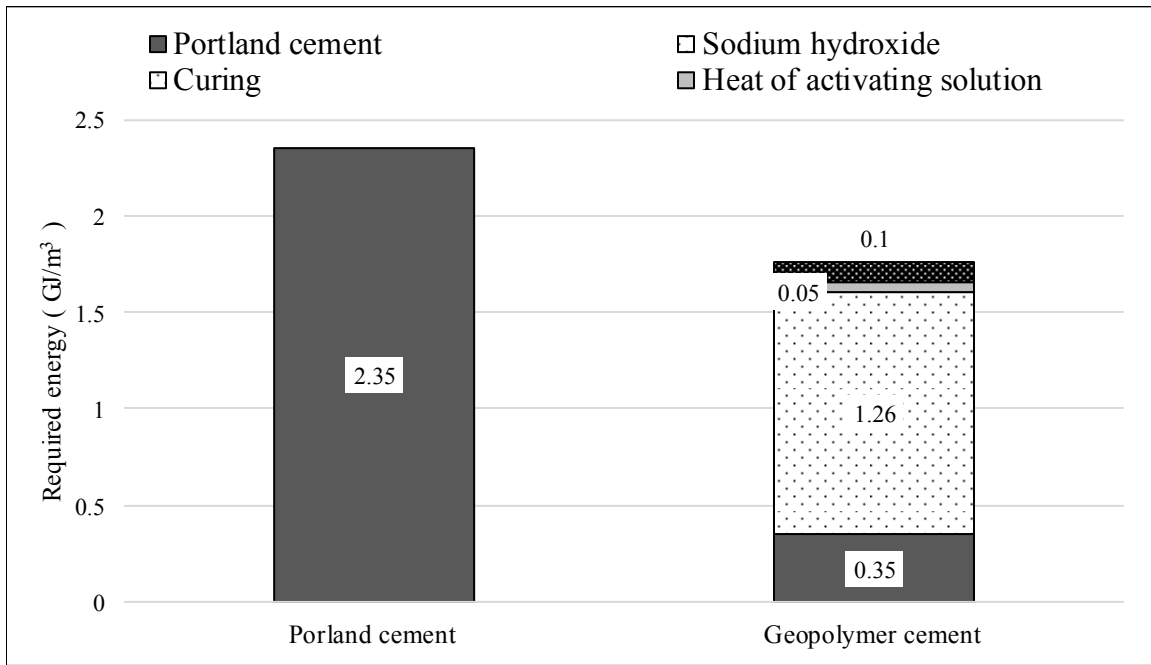


Figure 5.9 Thermal energy of 15% replaced Portland cement geopolymer concrete versus Portland cement concrete

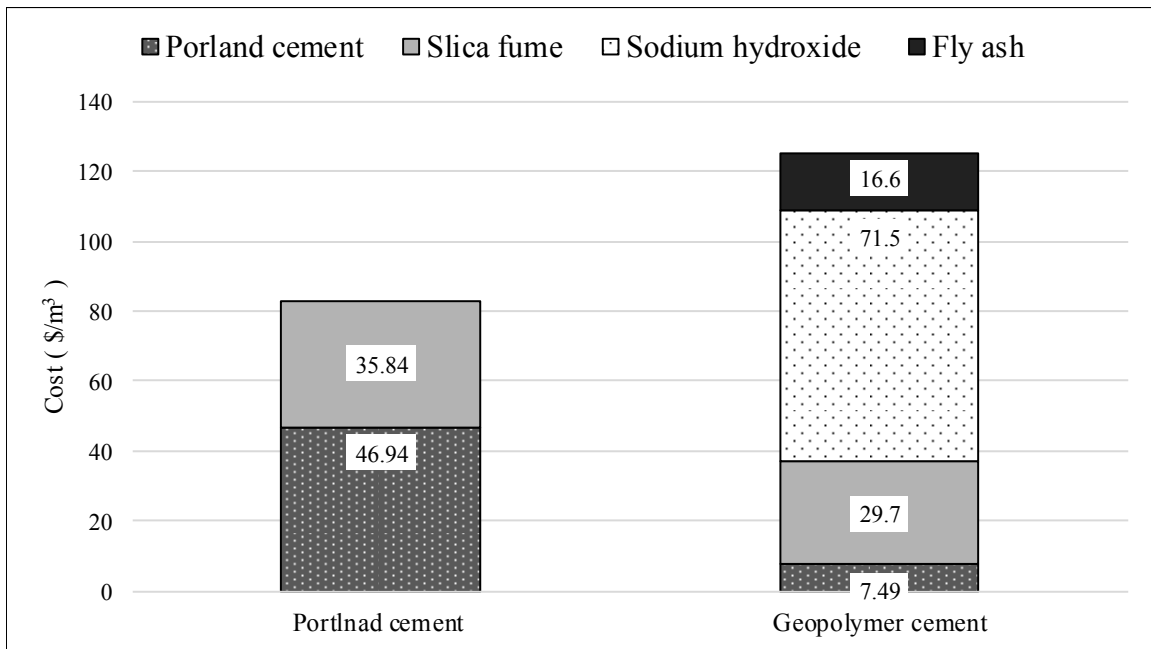


Figure 5.10 Cost of 15% replaced Portland cement geopolymer concrete versus Portland cement concrete

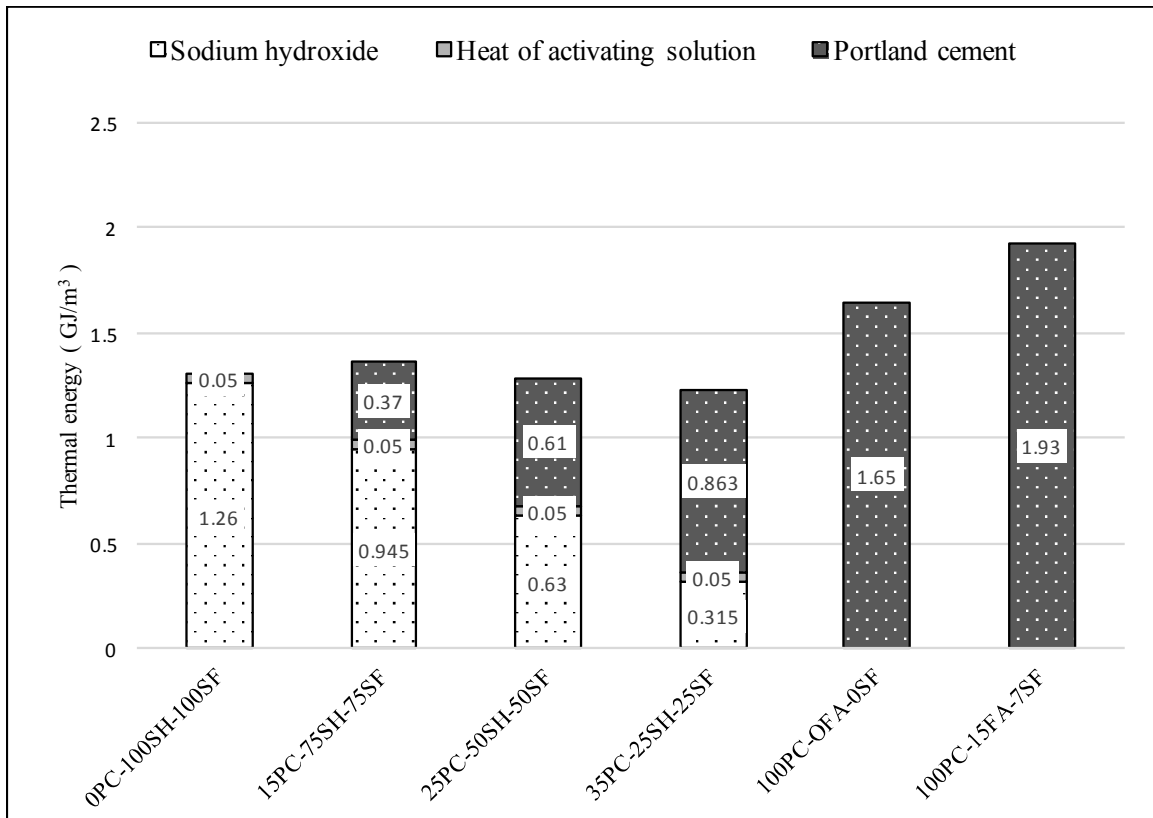


Figure 5.11 Thermal energy for mix 6-8 and their corresponding Portland cement

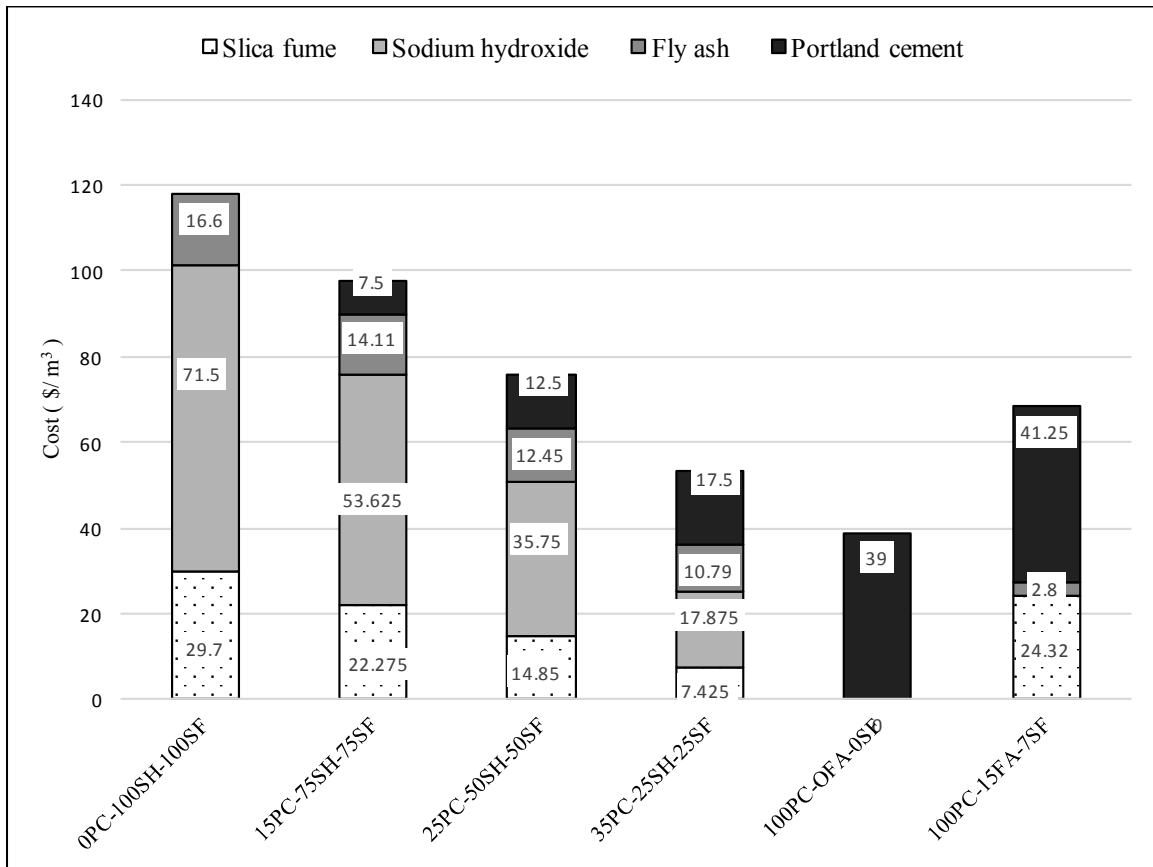


Figure 5.12 Cost of mix 6-8 and their corresponding Portland cement mixes

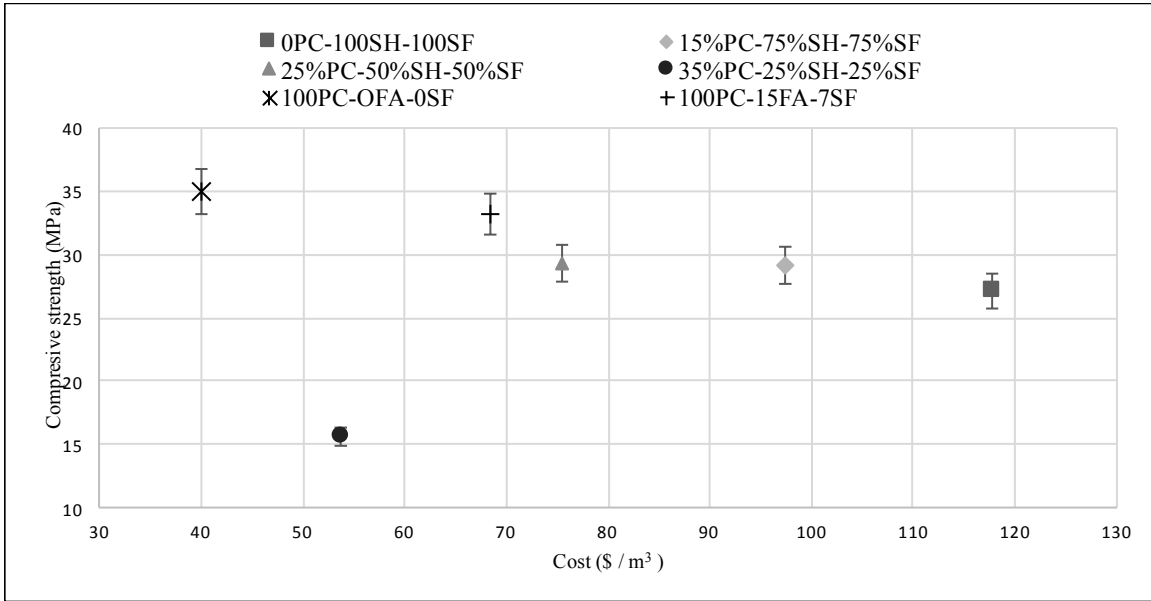


Figure 5.13 Compressive strength versus cost for mix 6-8 and their corresponding Portland cement mixes

CHAPTER 6  
MARKETING AND COMMUNICATION PLANS

## 6.1. Brief introduction

Any new company to start its business, it needs a startup budget. The startup budget can be a grant, cooperation with another company, or selling the startup up research.

Our mission is to provide precast, infrastructure, and construction companies with high-quality green cement. It has outstanding properties such as high early compressive strength, long-term durability, and environmentally friendly products, in comparison with Portland. Green cement not only reduces CO<sub>2</sub> emissions, but it also utilizes waste materials such as fly ash, slag, recycled aggregate, and metakaolin. With such high performances and properties and affordable price, we can be closer to our customers than before.

The benefits of our product are:

- Affordability (-20% - 15% difference in comparison with Portland cement)
- A different perspective on concrete (not only having promising properties but also helping future generation)
- Reduce CO<sub>2</sub> emissions
- Utilization of waste materials such as fly ash and slag
- Outstanding properties including excellent durability and compressive strength in comparison with Portland cement

- Does not require water for extended curing (less labor cost)

Properties:

- Resistance against acid
- Resistance against sulfate attacks
- High early age strength (can achieve 90% of the final strength in less than one day, the external heat is used)
- High performance in high temperatures
- High compressive strength
- Low permeability leading to enhance durability performance.

The product mantra “Together for a safe and strong future”

## **6.2. Situational analysis**

### **6.2.1. Market overview**

Our goal is to provide precast, prestressed, and other concrete members with high-quality environmentally-friendly cement. Our products have outstanding properties such as high early compressive strength, long-term durability, and environmentally friendly products, in comparison with Portland cement. It not only reduces CO<sub>2</sub> emissions, but it also utilizes waste materials such as fly ash, slag, recycled aggregate, and metakaolin. With such high performances and properties and affordable price we can be closer to our customers than before. Due to the global concern about greenhouse gasses, green cement can be an excellent solution to reduce CO<sub>2</sub> emissions and utilize numerous waste materials because concrete is the second most consumed material after water.

## **Competitors**

Our main competitors are divided into two different categories: green and Portland cement companies.

### **Green cement companies**

**Green and Gold concrete:** Green and Gold company, located in Wisconsin, provides green cement as well as durable concrete and some technical assistance. It dispenses ready-made concrete for purposes such as walkways, driveways, and patios.

**CERATECH:** This company provides a green, sustainable, and high-performance green cement. Incorporated in 2002, CeraTech converts some waste materials, such as fly ash, to useful products. It provides some technical input and conducts a variety of projects to develop green cement products.

**Carbon Cure:** This company retrofits concrete plants. It uses some waste or recycled materials such as carbon dioxide. It specifically uses carbon dioxide to reduce greenhouse gasses. The main operation process is to capture carbon dioxide and liquefy it so that it can be mixed with concrete.

### **Portland cement companies:**

**CNBM International:** CNBM is a global Portland cement company. Since 2004, their production has doubled in 5 successive years. Their clients and branches are distributed around 120 countries. The headquarter is in China. CNBM International company's production is around 200 million tons/year of Portland cement. It has more than 69 plants worldwide. The company is moving toward reducing the CO<sub>2</sub> emissions by



using alternative energy sources such as solar and wind power to run its industries. The company has started to pay attention to the business overseas.

**Heidelberg Cement Company:** This is one of the largest building material companies in the world. It was established in Germany and produces 118 million metric tons/year of Portland cement. It has more than 71 plants around the world. Heidelberg Cement Company has 62,000 employees working at more than 3000 production sites in 60 countries. The company specializes in providing and distributing aggregates in addition to the cement.

**CEMEX Company:** CEMEX Company is the global cement company established in Mexico. It has around 96 plants the world in 61 countries. It was founded in 1906. It provides technical service and construction materials including Portland cement. Some sustainable projects have been started to improve the quality of concrete and reduce CO<sub>2</sub> emissions in the CEMEX Company. Table 6.1 summarizes the sustainable and Portland cement company information.

### 6.2.2. SWOT analysis

The elements of a SWOT analysis for our product are:

**Strengths:** As engineers, we have the abilities to construct technically excellent material quality and properties. Our products are suitable for several applications such as sidewalks, roofs, precast walls, and prestressed elements. The green cement that we are producing not only has excellent performance, but it also can be used without a need for external heat. Green cement helps by utilizing large quantities of fly ash, which is stored around many power station plants in the United States. The quality of concrete that our company provides has many advantages such as rapid early strength gain, and high final

compressive strength after 28 days. In the case where external heat is used, the concrete that we produce can gain 90% of its final strength within 24 hours. The water absorption, permeable voids ratio test [ASTM C642] has shown that the absorption rate of our concrete products is much lower than Portland cement [9, 70]; hence, durability is more likely to be good. It is 20% less permeable than conventional concrete. The microstructure analysis showed that our concrete is denser and has lower microcracks which have a significant advantage in the long-term service life. In addition, we offer a green product which uses 40% less thermal energy than Portland cement concrete.

**Weaknesses:** Because green concrete is a new kind of cement, it would be hard to convince customers to use this product over established brands. The intense competition and strong established players are some of the concerns. The fluctuation of the price for materials would directly affect the price of our green cement.

**Opportunities:** There are broad potential applications for the green cement because the concrete demand is growing. The most related and convenient applications are the prestressed and precast applications because most of the structural members can be produced in a concrete plant in which the quality control will be higher. In addition, most of the prestressed and precast companies are equipped with heaters, which will accelerate the initial and final compressive strength. Countries, which have high coal combustion products such as China, the United States, and Russia will have great opportunity if a geopolymer product industry starts a business, because it will help to utilize the waste materials and reduce CO<sub>2</sub> emissions. Due to the global warming agreement in Paris for sustainable development, most developed countries will introduce regulations that will force the market to look for sustainable products. This will help to

increase our products' opportunities worldwide. Because the Green cement company will collaborate with LafargeHolcim incorporation, the startup and production facilities cost will be low. Based on our lab experiments for the green cement products that our company is providing, there is no need for water curing leading to less labor cost and water consumption.

**Threats:** The concrete market is very diverse and competitive. We face competition from both sides of the market; including green cement and conventional cement companies. Another potential threat is indirect competitors such as increasing demands on some waste materials such as fly ash.

### **6.3. Strategic insights**

#### **6.3.1. Product strategy**

Our products are suitable for several applications such as sidewalks, roofs, precast walls, and prestressed applications including wall panels and wall partitions. The green cement that we are producing not only has excellent performance, but it also can be used without a need for external heat. Our product helps by utilizing large quantities of fly ash, which is currently being stored in a way that can be harmful to the environment. The quality of concrete that our company provides has many advantages such as rapid early strength gain, and high final compressive strength in 28 days. For of external heat is used, the concrete that we produce can gain 90% of the final strength within 24 hrs. The water permeability is improved in relation to another type of concrete (20% less permeable than conventional concrete).

### **6.3.2. Marketing strategy**

#### **Product positioning**

Our customers have options, and our concrete and technical service can deliver on any front.

**Our company website:** Including technical service, cement, and concrete products will be provided through our company website. Our customer services on the website will answer all concerns related to the safety and environmental issues. Ready mix concrete will be available and can be ordered in most of our targeted places.

**Local companies:** Our products will be provided through some local companies, such as Columbia Precast Products. The green cement concrete with promising performance will be guaranteed for our contractors. Technical engineers will assist our customers through the website and the local companies as well. We are targeting the deserved trust that we will get the customers' feedback.

Recommended Target Market:

#### **Geographic segmentations**

- Major cities preferably close to fly ash source and electric power plants based on coal as the main source of energy
  - Milwaukee, WI
  - Charlotte, NC
  - Chicago, IL

- Cincinnati, OH
- Cleveland, OH, etc.
- Target market
  - Green cement products will focus on and target new construction companies. The reason is that most new businesses are willing to start with innovative materials. In addition, some of the new companies would like to cooperate to get materials without a need to pay up front, which our company will offer as an incentive based on the company's credit.

### **Psychographic segmentation**

Green cement concrete has remarkable performance and quality. These concrete products can be tailored to each individual to provide them with the best concrete and quality. Whom do we appeal to?

- Targeting market: Middle, Upper-Middle, and Upper class

“Social class can have a profound effect on consumer spending habits. Perhaps the most obvious effect is the level of disposable income of each social class. Generally, the rich person has the ability to purchase more consumer goods than those with less income, and those goods are of higher quality.” [74].

- Target Market: Active people and companies specifically, newly constructed buildings and corporations, which usually are willing to take a step forward.

### **6.3.3. Pricing strategy**

**Initially:** Competitive base pricing – We will assess our competitors' prices both directly and indirectly. We are new to the market and want to not only showcase that our green cement products are overall better products than our competitors but we also want to stay reasonable.

**Future:** We will move to more of a value based pricing once we have established a solid reputation for ourselves in the cement market and when we introduce new mix designs, which further develop our product properties, we will increase the price to reflect the perceived value of our product. The pricing strategy is shown in Figure 4.2. The pricing strategies may change based on marketing research. Specifically, if it recommends starting with value based pricing, this strategy will be the startup strategy.

#### **Local and website payment and price:**

**Value proposition:** Product leadership is strong and innovative turning trash into treasure and making an impact on the environment, and changing the way people build with a focus on customer intimacy. We will devote our main focus to promoting our product exclusively through civil engineering conventions as a superior concrete product.

### **Payment policy:**

We will require a 50% deposit to secure materials reservation. The remainder is required seven days before the construction date, prior to the materials shipment.

We accept PayPal and all major credit cards.

### **6.3.4. Marketing communication strategy**

#### **Short-term plan:**

- Analyze the collected data
- Conduct a survey to see whether targeted customers know about the product or not, are ready to accept it or not, and whether they know some information about it or not.
- Establish a website and record advertising videos
- Write copy for the website
- Write a list of website content details

#### **Midterm plan:**

- Goal: provide green cement, which not only reduces CO<sub>2</sub> emissions but also utilizes waste materials such as fly ash, slag, and metakaolin.
- Educate people about the green cement by product demonstrations, information sessions, etc.
- Target market: cement materials and construction companies
- The message that we are hoping to convey is “together for green and strong future”

General activities:

- Focus group with experienced construction and civil engineers (the goal is to understand their preference about the product properties and what obstacles are preventing them from switching to the green cement)
- Survey conducted in a concrete and construction conference
- A specific website dedicated to this kind of concrete (green cement)

Total budget:

- \$ 100,000-80,000 devoted to distribute surveys and conduct focus group

Advertising for the website on some internet sites, and videos of some massive concrete structures.

### **Marketing Objectives**

- **Inform**

Advise the world that a new and exciting product has hit the market using convention exhibits, sessions, workshop, newsletters and social media (see Appendix A).

- **Educate**

Inform the public on the many properties and qualities that our green cement has to offer (see Appendix A).



- **Awareness**

Demonstrate the vast difference in quality from our green cement products versus the competitors.

**Mode of Marketing Communication**

Our primary mode of marketing communication will be advertisements. We will target our market demographics via TV commercials, and the Internet.

- **Green cement company website:** In the website, the company will follow the style of cement companies. Because green cement company is a new company and the green cement is a new product in the marketplace, the website will display many figures and videos about the company and product. Engineers will have some videos to explain the products and their properties. The advantages of using green cement will have a wide space to be explained and current and new structures using green cement will be shown. Furthermore, customer service will have high attention to help our customers in using our products. The customer service will respond to customer's problems and send free samples to interested ones with perfect instructions about how to use the products. Because we have a new product, and customers are usually concerned about new product safety and credibility, a safety page will have good display on the website about the safety and many real examples about how outstanding our product is. The newsletter would be indicated on the website. The website will be used extensively for sales, marketing and finding shareholders who believe in our company's mission.

- **Facebook page:** In Facebook social media, the main target is collecting feedback from the customers. Many questions, which help to initiate the discussion between the customers, will regularly be posted. The green company will assign more than one worker to gather the feedback. There are several reasons for focusing on Facebook social media. First, it gives a chance for customers to comment and show their opinion and interest. It helps to investigate the market needs and awareness of the clients. Facebook will be used to advertise and describe briefly about green cement company current and new products. In addition, the Facebook page will be used to bring trafficking for the website and raise the interest in the green cement company products. Finding the lead will be a good option on the Facebook page as well.
- **Twitter:** Twitter will be used extensively for advertising and to raise awareness about CO<sub>2</sub> emissions problems and the potential solution for it. Because Twitter is a very popular social media in the United States, it will have enough attention in the social media department in the green cement company. Many embedded links will be used to advertise for the green cement company's website specifically as well as current products and future plans. Facebook links will be mentioned to lead the customer attention to the Facebook page and give them more space to show their opinion. The Twitter will be used to monitor other cement companies' activities. It will be used to bring the trafficking to the website and Facebook.
- **Digital signage:** Using digital signage is important in advertising. Digital signage is essential because it attracts customer attention, controls what is displaying, its ability to display anything that it intends to, and it is cheaper than papers and

other advertising methods. For our company, digital signage will deliver a specific message to the regular customers for future interests and experienced construction engineers. For instance, two signs will be displayed to inform ordinary people about green cement because the term is unknown to many people. Then, one signage to advertise the properties of and advantages of green cement in comparison with conventional concrete. The rest will be focused on the promotions and prices as well as reduction of greenhouse emission when using green cement or concrete. The font color will be green, and the logo will be displayed in the digital signage.

The digital signage will be displayed at the cities' entrance and industrial areas such as Cleveland, Charlotte, and Milwaukee.

Examples for what will be displayed:

1. Green cement not only reduces CO<sub>2</sub> emissions, but it also utilizes waste materials,
  - a. Note: the background color will be mostly green, chimney with some smoke will be used to represent the effect of CO<sub>2</sub> emissions as well as a picture of the earth with a green hand to represent green cement. The logo will be included.
2. Green cement has outstanding performance and rapid strength gains. Pictures of the products, and giant buildings will be displayed. Green background and some sustainability pictures will be shown.
3. You will not only get the perfect green product, but you will help the future generation to live in green nature. Same as previous picture, green background,

- and some pictures for nature and green cement products will be shown. The harmony between green cement and nature will be the main focus.
4. Affordable price, great performance, and durable structure, this is what green cement is all about. Green cement products for the affordable price will be shown. The logo and green background will be kept.
  5. As part of a corporation, our main target to make you happy and confident that what you will get more than expected. A sponsored logo will be displayed in addition to the green cement logo. Successful structure and nice smile people pictures will be displayed as well. The green cement company logo is shown in Figure 6.3.
- **Conventions and promoters:** We will hire a promoter to promote our product for buying at local universities, ACI conventions, and student competitions such as the concrete canoe.
  - **Store ad paper and magazine ad for purchase and rent**
  - **Professors/sustainability advocated celebrities:** Obtain an endorsement from a well-known professor or sustainable advocating celebrity promoting our product.

#### 6.3.5. Channel strategy

##### Online channel

Green cement concrete will be available to buy for individuals and construction companies via our online website. Customers will receive personalized quotes for the amount of cement or concrete materials that is needed. Company

owners and sustainable event coordinators can buy our green cement in bulk at a 15% discount rate when more than 200 tons of green cement are purchased.

All purchases must be completed online. Green cement company specializes in providing our customers with everything they need to construct safe and great structures. Our streamlined buying process ensures on-time shipping with four-day lead time order and is backed by a 100% satisfaction guarantee. The precast concrete products will arrive two days before each customer's date of construction starting, so that the customer may familiarize themselves with the product. Technical assistance will be available for the customer during the construction process. Our company website can be found at <http://www.greencementcompany.com/>.

#### **Local company contractor channel**

Our product positioning includes targeting local company contractors. Most local company contractors are tech-savvy and utilize the internet or social media outlets daily. Distributing on the internet via <http://www.greencementcompany.com/> and at technical workshops gives us a unique advantage.

#### **6.4. Marketing Research**

The research gathered for the launch of green cement includes the future forecast of sales global sales. We are still currently in the beta stage of launching, but we will be able to compete globally in the near future. We analyzed the data and determined that the concrete market is poised for high growth in the next few years. The chart below displays the global Portland cement market from the year 1998 to

2020. This chart displays unique insight into the potential growth of the cement and concrete market [75].

The main target of this research is to understand what the targeted customer wants and why or (why not) they prefer green cement. The customers would be encouraged to think globally about global warming and the effect of Portland cement on CO<sub>2</sub> emissions. In addition, the perceived message should be dedicated to showing how safe the green cement is compared with conventional cement as well as it will help to reduce the CO<sub>2</sub> emissions and utilize waste materials.

The main focus of the literature will be to investigate properties of green cement and Portland cement as well. The first direction will be mainly focused on studying the properties and performance of green cement. Particularly, it will focus on the advantages and disadvantages of concrete technology in case the green cement is used. The main pros and cons of Portland cement (conventional cement) will be studied. By doing so, the marketing campaign will focus on the real sights and can evaluate the cost and how the green cement can pick up its targets, consumers, and markets effectively.

In this plan, I am going to conduct a focus group with experienced construction civil engineers to understand what they are looking for specifically. In other words, the cost and properties of the Portland cement and green cement, advantages, and disadvantages from their perspective will be explained. Why they would or would not be willing to pay for competitive properties of green cement compared with Portland conventional will be discussed. In addition, there was an ACI conference held in Detroit, MI March 27-31, 2017. This conference is one of the largest concrete conferences in the world. It is the best way to communicate with concrete technology professors, students,

and construction companies. Many civil engineers and recruiters will be there to get updated with the best technology. Therefore, it is a good option to start conducting focus groups and to discuss the possibility of hidden problems with participants while exploring the best options for overcoming these obstacles.

In addition, field research with construction company engineers will help to expose us to the practical standpoint. It will also enable us to ask them why they prefer Portland cement and to get more information about preferred properties of Portland cement. The estimated cost is expected to average \$50 per person for coffee or dinner depending on the guest's preference, and for the cost of printing to collect as much as data as possible.

The focus group responses will be collected and organized depending on the categories including professors, and students will be mainly related to the properties and enhancements parts, and the cement companies' civil engineers will be moved into practical needs and required properties for the product to be ready to compete with conventional cement. Figures including bar charts and statistical distributions will be drawn up to help follow the main trends and divergence.

Furthermore, the videos for the website and advertisements will be shown to some experts to obtain their impression and to identify the main problems prior to the release on the company website and other sites. The literature will be studied, analyzed and organized to get some knowledge about properties of green cement and Portland cement.

Some of the focus group questions:

1. What do you like about Portland cement?
2. What do you think about green cement?

3. Why are you using Portland cement? Why do you prefer Portland cement?
4. What don't you like about Portland cement?
5. What don't you like about Green cement?
6. What else can you say about Portland cement?
7. What else can you say about green cement?
8. Is there anything else you would like to add?

## **6.5. Financials and Forecasts**

### **Target Market Research:**

Target market size for concrete and Portland cement demands for personal use has increased steadily over the past few years. Specifically, after the global economic crises in 2008, the Portland cement market increased and will be growing for the upcoming years. As shown in Figure 4.4, the global demands will reach 118,000 thousand metric tons. Global and United States markets will increase due to the economic growth in the United States and other countries.

Green cement company is expected to make a sizable splash in the market and will be recording significant growth within the first four quarters, as shown in Figure 6.5. The next year, Green Cement Company fluctuates on whether or not to introduce a new product for a higher price. Green Cement Company will most likely launch a newly improved Green Cement product for sale on the market at the price of \$130.99, \$90.99, and \$70.99 per metric ton. Initially, we expect a brief decline in sales, but we expect to quickly recover and produce more profit than we have in the previous years.



The estimates seen in the table are derived from some relevant market research that suggests that because of the competition in the market, Green Cement Company will most likely start selling small volumes of the concrete product, but as the market grows, so will our profit and volume.

**Tables:**

Table 6.1 Green and Portland cement companies

| Company name             | Production (Mt/yr)             | Application                                 | Sustainable |
|--------------------------|--------------------------------|---|-------------|
| Green and Gold concrete  | Local production<br>Few amount | Driveways, patios,<br>walkways              | Yes         |
| CERATECH                 | Local production<br>Few amount | Carbon neutral<br>cement                    | Yes         |
| Carbon Cure              | Few amount                     | Purified and<br>liquified CO <sub>2</sub> , | Yes         |
| CNBM international       | 200                            | Most of the<br>applications                 | No          |
| HeidelbergCement company | 118                            | Most of the<br>applications                 | No          |
| CEMEX Company            | 96.0                           | Most of the<br>applications                 | No          |

Table 6.2 Price strategy for 1 cubic meter of concrete

|   |                          |
|---|--------------------------|
| Cost of Goods Sold for the Standard mix:  | \$120                    |
| Overhead Cost                             | \$10.0                   |
| Cost of Goods Sold for the Standard mix 1 | \$95.0                   |
| Overhead Cost                             | \$9.00                   |
| Cost of Goods Sold for the Standard mix 2 | \$78.0                   |
| Overhead Cost                             | \$8.00                   |
| Cost of Goods Sold for the Standard mix 3 | \$56.0                   |
| Overhead Cost                             | \$7.00                   |
| Retail Price for the standard mix:        | <u>\$120</u>             |
| Potential Gross Profit                    | ~ \$15.9 per cubic meter |

**Figures:**

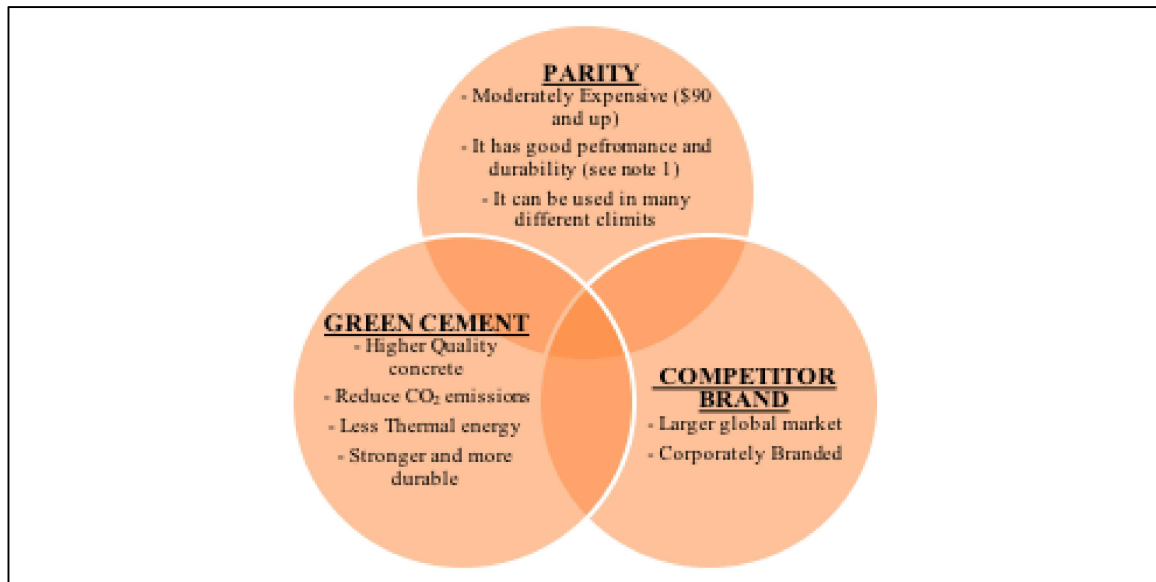


Figure 6.1 Points of Parity and differences (green and conventional concrete companies)

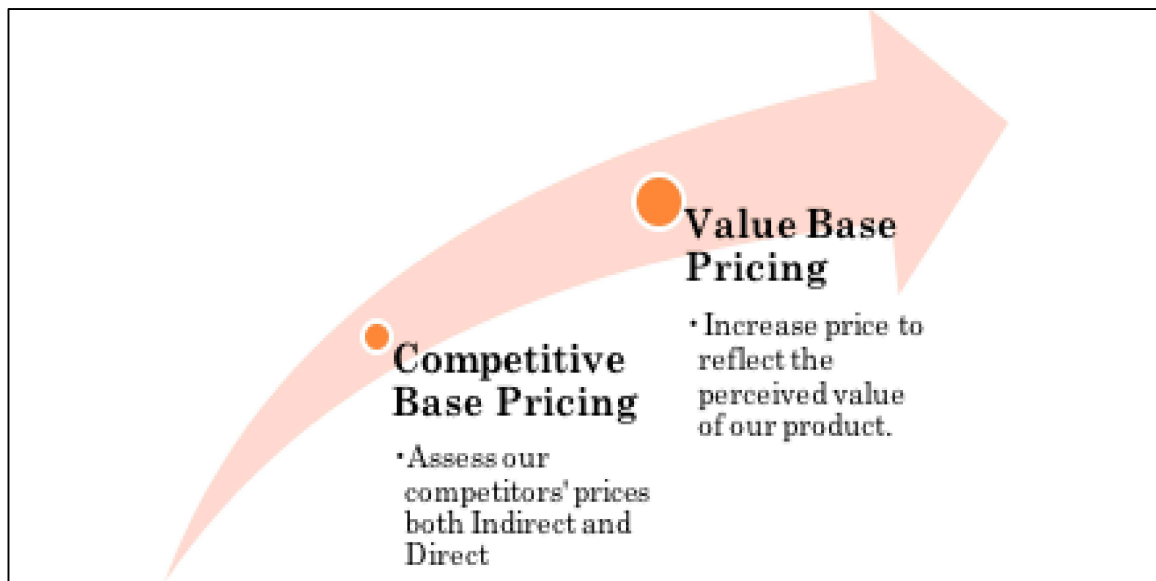


Figure 6.2 Pricing strategy



Figure 6.3 Green cement company logo

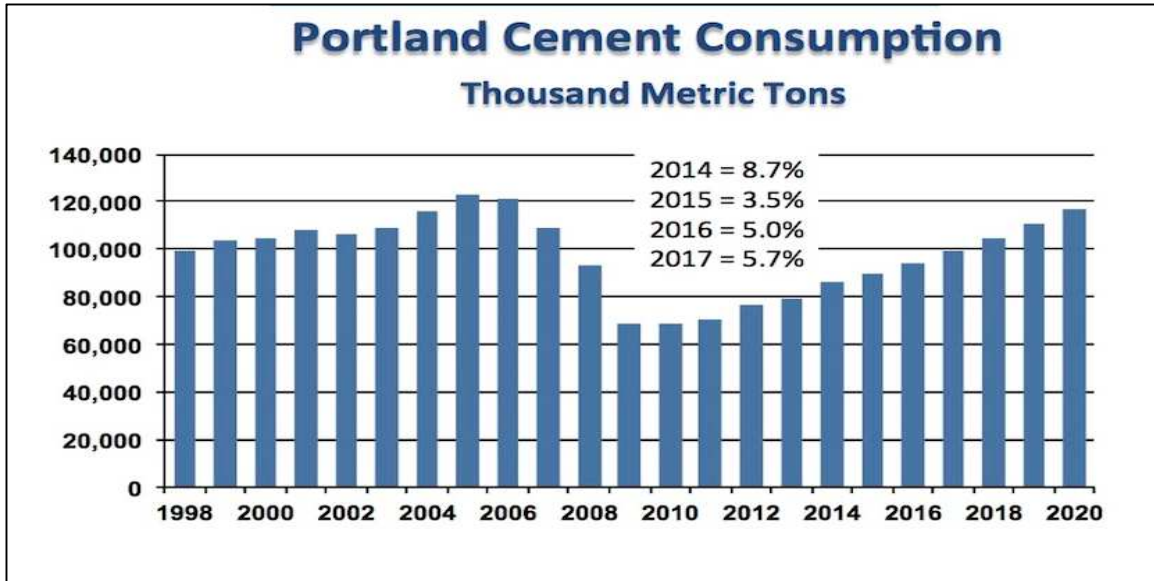


Figure 6.4 Global Portland cement market from year 1998 to 2020

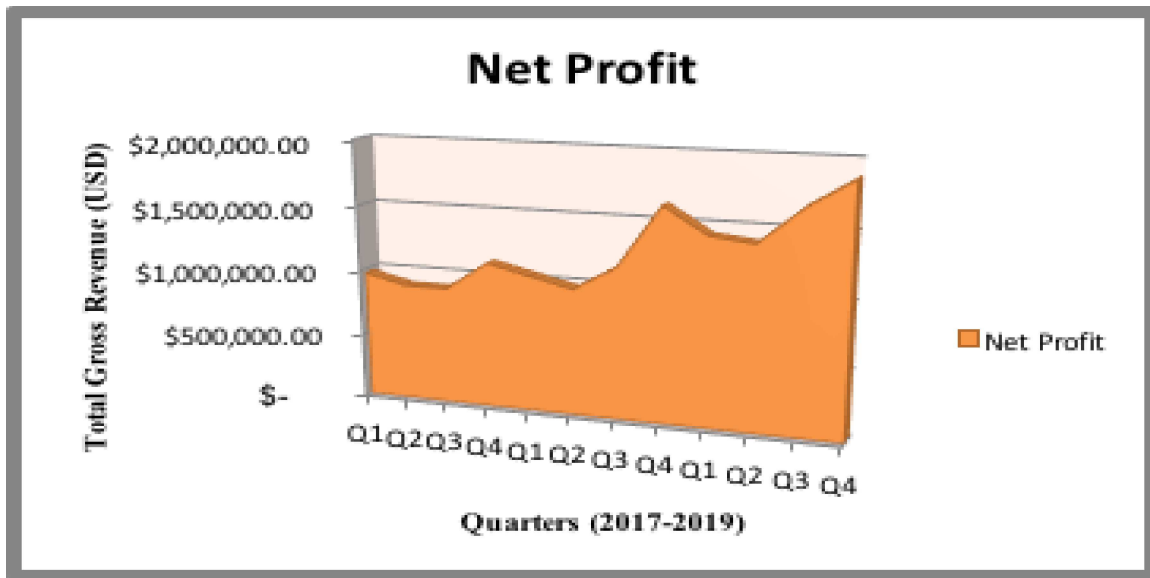


Chart 6.5 Net Profit for Green Cement Company (Q1-Q4 for years 2018-2019)

CHAPTER 7  
CONCLUSIONS AND FUTURE WORK

## 7.1. Conclusions

1. Geopolymer concrete has a lower fuel (thermal energy) usage than Portland cement by 52 %.
2. Sodium hydroxide plays a dominant role not only in fuel usage but also in the cost of geopolymer concrete.
3. The current cost of geopolymer cement is around \$117 per ton, while the compressive strength was 107 MPa (15,400 psi)
4. Using Portland cement as a replacement improves the compressive strength, and eliminates using external heat, while it has a small effect on the overall cost and energy usage.
5. Reducing sodium hydroxide concentration helps to reduce the cost up to \$82 per cubic meter, and it has a big impact on the fuel usage. Therefore, reduction of sodium hydroxide concentration should be the main focus in future research.
6. The three mix designs reduced the cost of geopolymer concrete up to 50% in comparison with the standard mix, while the mechanical and fuel usage are good.
7. The marketing plan showed that geopolymer concrete can be profitable business to be initiated specifically in the North of the United States.

8. Communication campaigns suggest that raising the awareness of people about CO<sub>2</sub> emissions issues, and informing them about how much the green cement (geopolymer cement) can be the perfect solution would help to enlarge the success of the green cement business.

## **7.2. Future work**

- Calculating the effect of transportations on the cost, fuel (thermal energy) usage, and CO<sub>2</sub> emissions.
- Calculating CO<sub>2</sub> emissions and comparing this with Portland cement, and finding the potential ways to reduce it.



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## APPENDIX A

### NEWSLETTER



*Green cement helps to reduce CO<sub>2</sub> emission by 80-90%.*

*Green cement company mission to provide environmentally friendly cement with exceptional properties.*

*Our mission to provide high quality concrete and cement with affordable price.*



Upcoming events: Green cement convention in Ohio in November 16, attending ACI convention in Detroit in Spring 2017.

#### **Our mission**

As part of LafargeHolcim, our mission is to provide precast, infrastructure, and constructions companies with high quality green cement. It has outstanding properties such as high early compressive strength, long term durability, and environmentally friendly products, in comparison with Portland. A harmony between concrete structure, including buildings, bridges and sidewalks, green nature, and human is our mission. Finding an environmentally friendly concrete with superb mechanical and physical properties is our specialty.



Image 1: Green cement product as sidewalks

## Waste materials productions

- *Green cement reduces CO<sub>2</sub> emissions, and utilizes waste materials such as fly ash.*
- *Fly ash production is 50% higher than its consumption.*
- *The waste materials have potential effects on human, planet, and animals.*
- *Fly particles can penetrate and effect on the underground water.*



The coal production is 50% more than its utilization worldwide, and this leads to a numerous amount of waste materials. The green cement is the solution to use such as massive amount of waste material and convert it to useful materials.

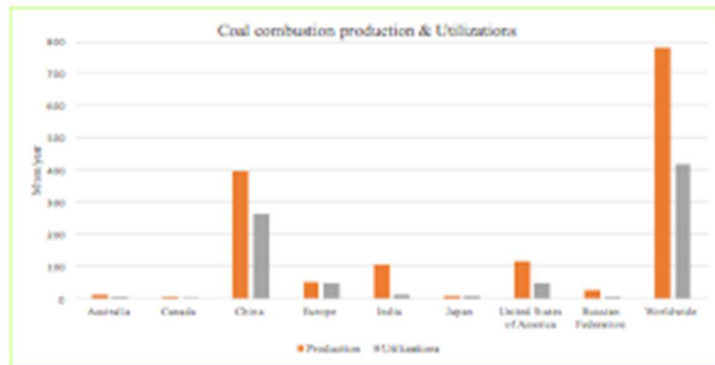


Figure 1: Coal, which has 80% fly ash, production (Heidrich and et al, 2010)

## Waste materials effects:

Waste materials such as fly ash, has a potential effect on the human, animals, and plants. The underground water will be affected due to storing the fly ash underground as well as air will be contaminate due to fly ash fine dust if it is stored outside



Image 2, Fly ash outside storage site

### **Green Cement Products:**

With 40% higher performance in comparison with conventional concrete, our products show outstanding properties compared with Portland cement. The rate of compressive strength gain is rapid which is good for the prestressed concrete application. The fire resistance is outstanding and it takes long time to show a good performance. The permeability is very low and can be lowest in case the low permeability was the main interest.

### **Contact information of manager of product technicians and editor**

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