

# Compressive Strength and Embodied Energy Optimization of Fly Ash Based Geopolymer Concrete

**Brett Tempest<sup>1</sup>, Olanrewaju Sanusi<sup>1</sup>, Janos Gergely<sup>1</sup>,  
Vincent Ogunro<sup>1</sup>, David Weggel<sup>1</sup>**

<sup>1</sup>University of North Carolina at Charlotte, Department of Civil and Environmental Engineering, 9201 University City Blvd, Charlotte, NC 28223

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## ABSTRACT

Geopolymer cements can be used to produce structural strength concrete without the considerable carbon dioxide emissions that characterize Portland cement manufacture. Geopolymers are formed when alumino-silicates, such as fly ashes, dissolve in a strong alkaline solution, reorganize and precipitate in a hardened state. The economical and sustainable production of geopolymer cements for structural uses hinges on minimizing the quantity of high energy materials, like NaOH, required to activate the fly ashes. This paper details the optimization of the mix design and curing regimen for a geopolymer concrete by relating strength development to the quantity of energy that is consumed to activate the fly ashes and curing the concrete at elevated temperatures. The concretes were produced with the addition of NaOH at the rate of 10%, 13% and 16% of the fly ash mass. Cylindrical samples (76mm diameter by 152mm height) were made and aged in batches at room temperature and then cured at 75° C. The duration of the aging and curing process was manipulated to determine the most effective combination for developing compressive strength. The compressive strength of samples from each batch was measured at 28 days and the results were used to optimize the mix design. The material and energy inputs for the optimized geopolymer concrete are compared to Portland cement concrete of equivalent compressive strength.

## INTRODUCTION

As worldwide awareness and concern over global climate change increases, the greenhouse gas intensiveness of Portland cement manufacture is attracting scrutiny. A viable replacement, geopolymer cement, is currently receiving increased attention in academic and industrial communities for its ability to serve as a binder in structural concrete applications. Geopolymers are formed when alumino-silicates dissolve in a strong alkaline solution, reorganize and precipitate in a hardened state <sup>1,2</sup>. The term “geopolymer” was coined by Davidovits following research into inorganic-polymer technologies for industrial applications <sup>2</sup>. Geopolymers have been manufactured from

alumino-silicate rich industrial wastes, such as blast furnace slag, for more than 60 years and are also often referred to as alkali-activated cements or inorganic polymer cements<sup>1</sup>. The bulk of research into the use of industrial waste in these cements has centered on fly ash due to its abundance and the current scarcity of useful applications for it relative to the quantities produced<sup>1,3-10</sup>. Geopolymer cement concrete can have properties very similar to Portland cement concrete when formed under suitable conditions<sup>11</sup>. In addition to providing a gainful use for waste material and reducing greenhouse gas emissions, the geopolymerization has also been shown to immobilize some heavy metals present in fly ashes<sup>12</sup>.

The preparation of geopolymer cement concretes has been accomplished by mixing the aluminosilicate source material (typically fly ash or metakaolin) with an “activating solution” that contains the alkalinity, and sometimes a supplementary source of soluble silicate. Following the addition of the activating solution, the concrete is mixed and finally cured under suitable conditions. The nature of these conditions depends on the chemistry of the source material and the activating solution. Besides the material inputs and curing requirements, geopolymer cement concretes are mixed and used in a similar fashion to Portland cement concretes.

Geopolymer cements have been used to create structural concretes by Hardjito and Rangan<sup>13</sup>. In the course of their preliminary research, mixing procedures similar to those common for Portland cement concrete were used. It was also discovered that superplasticizers could be used effectively. Concretes were produced with compressive strength in the range of 44-90 MPa<sup>13</sup>.

The process of curing and hardening is different for geopolymer cement concrete than for Portland cement concrete. Geopolymers tend to increase in strength following a period of curing at elevated temperatures, ranging from room-temperature to nearly 100° C depending on the source materials and strength development requirements. Temperature has been found to affect setting time, the pore structure and the development of strength. Sinhunata et al. found that the geopolymerization reaction proceeded more quickly at elevated temperatures<sup>14</sup>. As temperatures increased from 30 to 50 to 75° C the Al and Si precursors were more readily dissolved from the source material. The apparent setting time was also found to decrease as the temperatures increased<sup>14</sup>.

Alonso and Palomo also studied the effect of heat addition to the geopolymer gel and found that increased temperatures accelerated the reaction and promoted hardening<sup>15</sup>. Using isothermal calorimetry, the heat evolution was monitored from the initial contact between activator and metakaolin through the end of the geopolymerization process. An exothermic peak corresponding to condensation occurs earlier as the ambient temperatures increase from 35 to 60° C<sup>15</sup>. Some studies have related curing time with temperature. Swanepoel et al found that an optimum strength was achieved by curing fly ash based geopolymer at 60°C for 48 hours<sup>16</sup>. However, a study by Xie and Xi developed much stronger pastes with different materials by curing under the optimal temperature of 55°C for only 12 hours. Others have developed geopolymers with

compressive strengths suitable for structural application through room temperature curing<sup>9</sup>.

Another aspect of geopolymer preparation that has impacts on strength development is the selection of an activating solution. Researchers have used potassium hydroxide (KOH) as well as sodium hydroxide (NaOH) for alkalinity. NaOH is generally favored for its greater efficiency in liberating aluminate and silicate from the source material, as well as its economy. Increased alkali concentration results in greater solubility of the source material<sup>17</sup>. However, an excess of alkali hydroxide or of soluble silicate tends to retard strength development. Sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) is also a preferred activating solution due to its soluble silicate content, which tends to increase the rate of the polymerization reaction. Previous, unpublished research at UNCC has shown that activating solutions containing more than NaOH/Fly ash ratios greater than 0.16 are typically difficult to work with. Concretes made with these activators tend to exhibit poor workability and often set-up erratically before cylinder specimens can be created.

It has been shown that curing temperatures as well as the type of activating solution have an interrelated role in determining the workability and strength development of geopolymer cement concrete. Thus, the curing routine must be matched to the activating solution and the aluminosilicate source material. This interrelation provides opportunities to optimize the production process for geopolymer cement concrete in order to reduce the total energy required to produce material of a particular strength.

## EXPERIMENTAL PROGRAM

Three batches of geopolymer cement concrete were prepared using the proportions given in Table 1. The concrete was mixed in  $0.05 \text{ m}^3$  batches in a  $0.085 \text{ m}^3$  rotary mixer by mixing the dry ingredients for two minutes and then adding the activating solution for five additional minutes of mixing.  $76 \times 152 \text{ mm}$  cylinders were prepared by adding the concrete in three lifts and rodding 25 times per lift with a 9.5 mm diameter rod. For consistency, the step of vibrating all the cylinders for 1 minute after rodding was added.

The fly ash used in this study was sourced from a southeastern steam station. X-ray fluorescence (XRF) analysis was used to determine the composition and results are presented in Table 2. Aggregates used in the study were secured from a local quarry. Coarse aggregates were granitic with 9.5mm maximum nominal diameter. The gradation for both fine and coarse aggregates is given in Table 3.

Table 1: Mixing proportions kg/m<sup>3</sup>

<i>Mix #</i>	<i>Fly Ash</i>	<i>Water</i>	<i>NaOH</i>	<i>Silica Fume</i>	<i>Fine Aggregate</i>	<i>Coarse Aggregate</i>
1	495	163	49.5	37.1	793	793
2	474	163	61.6	46.2	793	793
3	455	163	72.7	54.5	793	793

Table 2: XRF analysis of fly ashes

Oxide	% by Mass
SiO <sub>2</sub>	56.20
TiO <sub>2</sub>	1.46
Al <sub>2</sub> O <sub>3</sub>	28.00
Fe <sub>2</sub> O <sub>3</sub>	5.22
MnO	0.02
MgO	1.00
CaO	1.52
Na <sub>2</sub> O	0.21
K <sub>2</sub> O	2.74
P <sub>2</sub> O <sub>5</sub>	0.18
Totals	96.55
LOI	3.32

Table 3: Gradation of aggregates

Sieve [mm]	% finer	
	Coarse Aggregate	Fine Aggregate
16.0	100.00	100.00
12.5	99.50	100.00
9.50	85.30	99.77
4.75	28.80	99.54
2.36	5.50	97.94
1.18	1.30	90.37
0.425	0.70	37.16
0.300	0.70	19.95
0.150	0.50	1.61
Pan	0.00	0.00

The cylinders were aged and cured according to the schedule presented in Table 4. The aging process occurred under ambient conditions in the Structural Materials Laboratory at UNC Charlotte. After the cylinders were made, the 0-hour aging batch was placed directly in a 75° C curing oven. The other cylinders were left out in the lab and added to the oven after either 24 or 48 hours of aging. Cylinders were demolded immediately after the requisite period of curing and were stacked on a pallet under the ambient conditions in the lab until testing on the 28<sup>th</sup> day. From each batch and curing group, three cylinders were tested in compression in accordance with ASTM C39<sup>18</sup>. The procedure was carried out on a universal testing machine at UNC Charlotte.

Table 4: Number of cylinders made with each aging and curing regimen

Aging	Curing	
	24 hours	48 hours
0 hours	10	10
24 hours	10	10
48 hours	10	10

## RESULTS

The compression tests revealed that the material strength ranged from a minimum of 32.5 MPa to a maximum of 67.5 MPa. The results show that strength development is related to all three variables that were manipulated in this experiment: activator concentration, aging time and curing time. These results verify trends found by other researchers as well as provide insight into their interrelation.

The average mix strength was highest for the Mix #2 group and lowest for the Mix #3 group. Thus, strength seemed to improve when the alkalinity of the activating solution was increased from 10% NaOH/fly ash to 13% NaOH/fly ash, but declined when the alkalinity was further increased to 16% NaOH/fly ash. Despite these general trends with strength development related to the alkalinity of the activating solution, there is an important influence from the aging and curing schedule.

The results presented in Table 5 show two main trends in strength development for the aging and curing routines used in this course of experiments. Increasing aging time from 0 to 2 days improved the 28-day compressive strength in all cases. Increased curing time at 75° C also improved the 28 day strength in all cases. These results are illustrated in Figure 1. For the Mix #1 specimens, high temperature curing for an additional day improved the compressive strength an average of 12%. For these same specimens, the impact of additional aging was an average of 6% increase in

compressive strength. For the Mix #2 specimens, the effect of additional high temperature curing time was an average compressive strength increase of 13%. The impact of additional aging time on these specimens was an increase of strength by 8% on average. Mix #3 showed the greatest improvement in strength with both increased aging time and 24 hours of curing. However, the maximum strength attained is that achieved by Mix #2.

Figure 1 also shows that there might be room for further improvement in compressive strength by aging the specimens for more than two days prior to heat curing. Whereas the improvement in strength for Mix #1 has leveled off by day two, Mixes #2 and #3 appear to still be increasing at day two. Further experimental work would be required to examine this trend.

Table 5: Results of compression and tension tests

Mix #	Aging Time [days]	Curing Time [hours]	$f'_c$ [MPa]
1	0	24	37
1	0	48	41
1	1	24	41
1	1	48	45
1	2	24	41
1	2	48	48
2	0	24	51
2	0	48	55
2	1	24	53
2	1	48	64
2	2	24	57
2	2	48	67
3	0	24	32
3	0	48	44
3	1	24	43
3	1	48	47
3	2	24	55
3	2	48	56

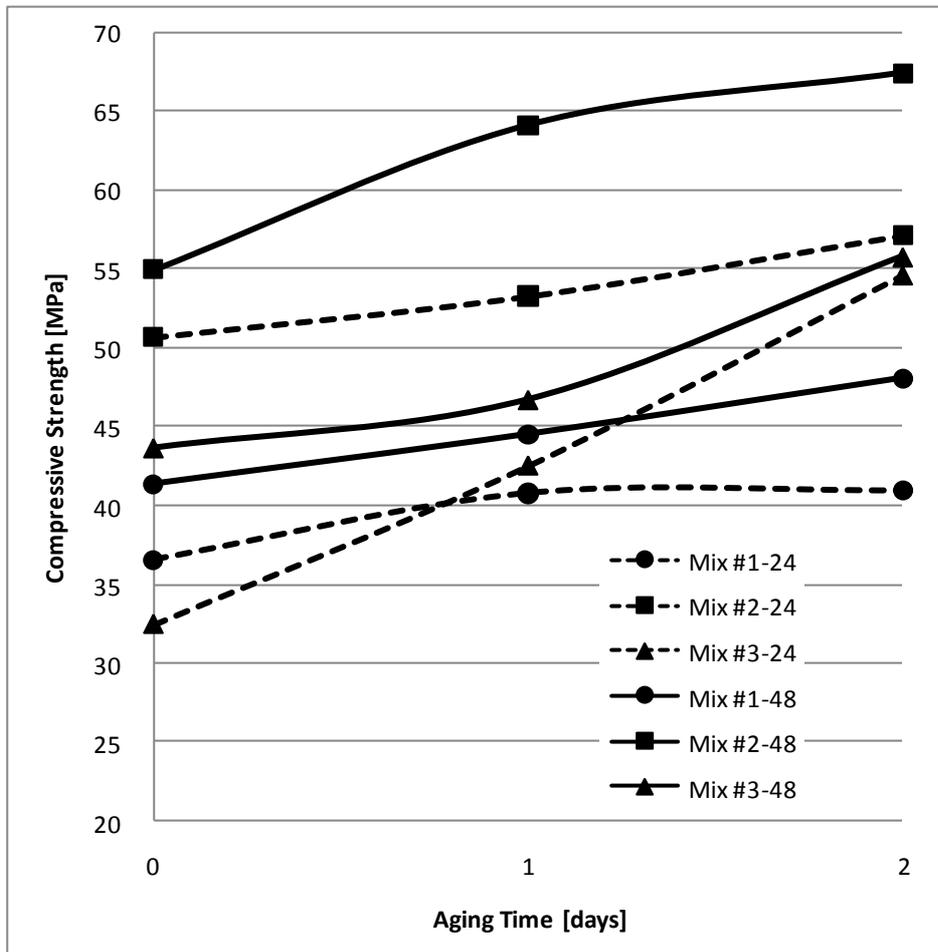


Figure 1: Compressive strength development with aging and curing time

The benefit of aging for longer periods versus curing for longer periods is demonstrated in Figures 2, 3 and 4. Mixes #1 and #2 both showed compressive strength gains of approximately 25% through the combination of increased aging and curing periods. By comparing the batches that were aged for 0 days and cured for 24 hours with those aged for 2 days and then cured for 24 and 48 hours, it is possible to determine the effect of each process on the final strength development. These differences are illustrated in Figure 2 by the regions labeled “A” and “B.” Region “A” is the difference in compressive strength of cylinders that were aged for 0 days and cured for 24 hours and the strength of cylinders that were aged for 2 days and cured for 24 hours. Thus, it describes the effect of two days of aging time. Region “B” quantifies the difference in compressive strength of cylinders aged for two days and cured for 24 or 48 hours. For Mixes #1 and #2, 38% of the gains between the batch not aged and cured for only 24 hours and the batch aged for two days and cured for two days were related to aging while 62% were related to heat curing. The higher alkalinity Mix #3 showed much

different behavior with 95% of the strength gains being attributable to aging and only 5% attributable to heat curing.

It would appear that heat is playing a role in two different reaction mechanisms. For instance, in the lower alkalinity concretes, the heat might help strength development by improving the dissolution processes by increasing the solubility of silica. In higher alkalinity systems the heat is probably not required to improve dissolution due to the greater quantity of available OH<sup>-</sup> ions. This may be explained by the very small difference in strength between Mix #3 specimens aged for 2 days and cured for 24 hours versus those cured for 48 hours.

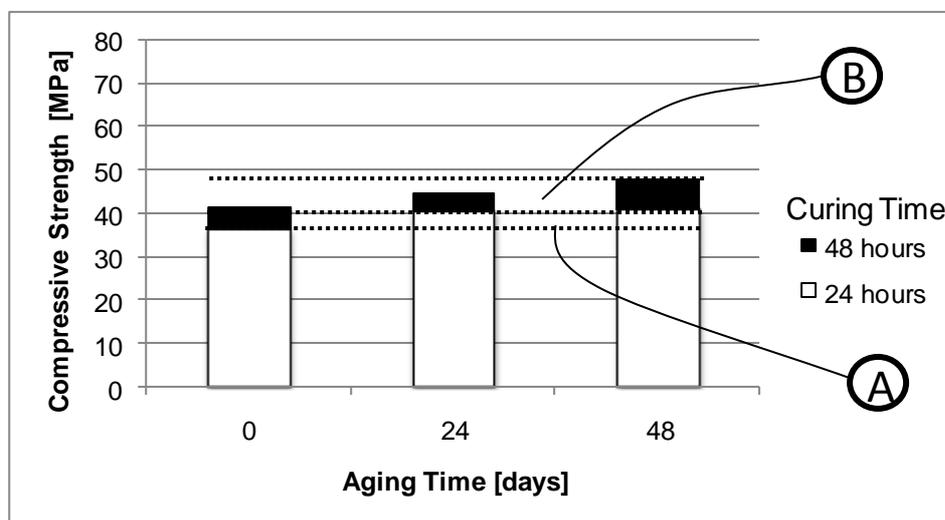


Figure 2: Compressive strength after 24 and 48 hours of curing for Mix #1

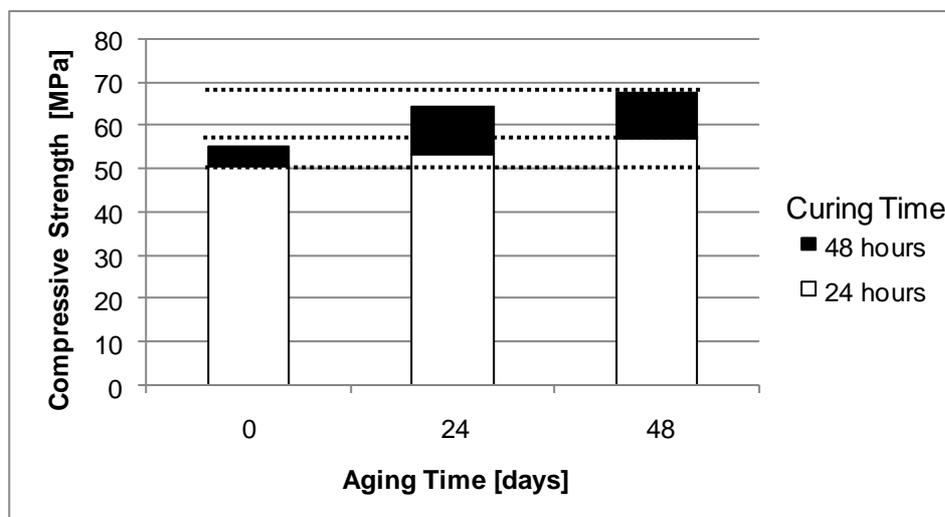


Figure 3: Compressive strength after 24 and 48 hours of curing for Mix #2

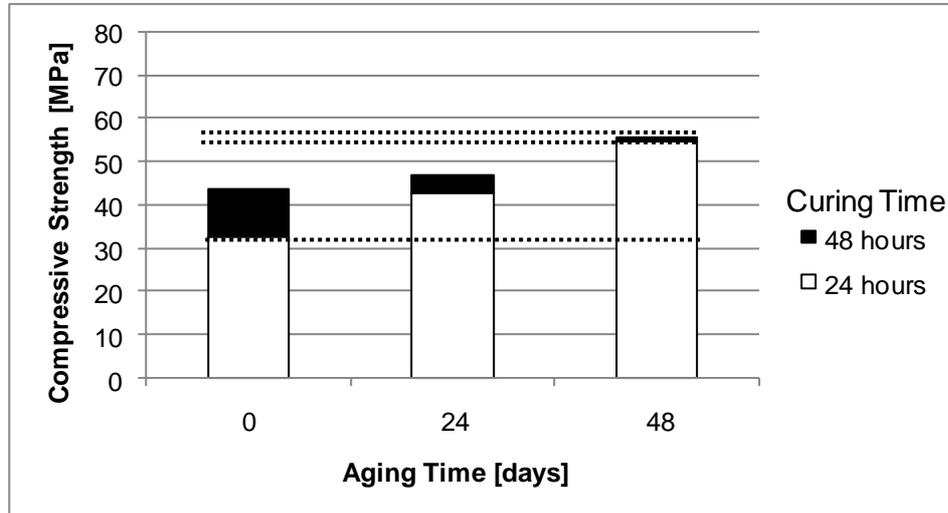


Figure 4: Compressive strength after 24 and 48 hours of curing for Mix #3

## ENERGY REQUIREMENT FOR GEOPOLYMER CEMENT CONCRETE

As an industrial process, the production of geopolymer concrete must be made as economical as possible with regard to energy and material inputs. From a sustainability standpoint, geopolymer concrete can only be considered as an option for green construction if the processes used to manufacture it do not cause unacceptable harm to the environment, depletion of resources or damage to human health. For the purposes of evaluating sustainability, life cycle assessment is often used to quantify all the inputs and outputs required to manufacture, maintain and dispose of a product or material. A full life cycle analysis is beyond the scope of this paper. However, to determine the most efficient manner by which the compressive strength of the geopolymer concrete specimens can be improved, an energy assessment was performed on a hypothetical production technique.

The analysis was performed on a hypothetical technique because the actual inputs and outputs in an industrial setting are not known very precisely for geopolymer concrete. As industrial scale processes are perfected, the conservative values used here will be refined. The values used here are assumed or extrapolated from those determined in the lab according to the following methodology. The processes examined are: 1) production of the alkalinity source, NaOH, 2) the production of the activating solution by mixing silica fume with NaOH and water and heating for 24 hours, 3) high temperature curing.

In this study, the energy required to produce geopolymer concrete is ultimately compared to that required to manufacture Portland cement concrete of similar strength.

In order to compare the results of a life cycle analysis for different materials, it is necessary to define a functional unit. This is an especially critical step when comparing radically different systems, such as timber columns versus steel columns. But, since concrete bound with geopolymer cement can be used in an overwhelmingly similar capacity as precast Portland cement concrete, the functional unit used for this analysis is simply 1 m<sup>3</sup> of 70 MPa concrete. The two materials can be cast into identical shapes that can be expected to offer similar structural performance. Therefore, the energy comparison that is presented is solely related to the development of the concrete strength and does not include the energy required for other concreting practices. The main differences in the two processes relate to the preparation of the cement. In the case of Portland cement, manufacturing energy is applied prior to mixing the concrete. For geopolymer cement, the energy used to develop strength is applied to prepare the activating solution and to heat the concrete after it is mixed and placed. However, the mixing processes, formwork preparation, reinforcing requirements, concrete placement and consolidation practices are very similar.

### *Energy Requirements*

The energy necessary to collect fly ash and silica fume used to produce geopolymer was neglected from this study. Because these are both industrial byproducts that must be collected for compliance with air quality regulations, it is typical to neglect their upstream energy requirements. An important energy input to the use of these materials is that for transportation. However, since transportation energy is not considered in the comparison of geopolymer cement concrete with Portland cement concrete production, it is left out of the analysis altogether. Also not considered are the energy requirements for making the concrete admixtures used because their quantities are small enough as to not be significant in the overall analysis.

Phase 1, production of alkalinity source:

NaOH is most commonly produced by electrolysis of brine solution. The reaction produces chlorine gas at the anode and a weak alkali at the cathode. The alkaline solution is typically concentrated to 50% strength for shipment. The SPLINE LCA dataset quantifies the energy required to produce sodium hydroxide as 20.5 MJ/kg<sup>19</sup>.

Phase 2, production of the activator solution

The method of producing alkaline activator solution for the concretes made in this set of experiments was to mix water, silica fume and the sodium hydroxide together and then to heat the solution overnight. To estimate the energy required for this process only the energy required to maintain an elevated temperature of 75° C in a well insulated tank was included. The energy required to heat the solution to 75° C was not included because the dissolution of the sodium hydroxide in the water produces temperatures that far exceed 75° C. The reaction with the silica fume is also quite violent and elevates the temperature further. It was estimated that a well insulated tank will lose

heat energy at the rate of  $0.194 \text{ MJ m}^{-2} \text{ h}^{-1}$  when the contents are maintained at  $75^\circ \text{ C}$  and the ambient conditions outside the tank are  $21^\circ \text{ C}$ . In the lab, small quantities of activator are produced in an oven. However, in an industrial setting it would be produced in a much different manner. In this experiment, the quantity of activator solution required to produce  $1 \text{ m}^3$  of concrete is about 100 L. A cylindrical 100 L tank with a height twice its diameter would have a surface area of  $1.25 \text{ m}^2$ . Thus, the energy required to maintain the sodium silicate solution at  $75^\circ \text{ C}$  for 24 hours would be 5.8 MJ.

### Phase 3, High temperature curing of geopolymer

In the absence of measured quantities, the specific heat of geopolymer concrete was assumed to be similar to that of Portland cement concrete,  $0.88 \text{ J G}^{-1} \text{ K}^{-1}$ . Other researchers have determined the specific heat of geopolymer-sand mortars to range between 0.7 and  $1.0 \text{ J G}^{-1} \text{ K}^{-1}$ <sup>20</sup>. As the bulk of constituents in both materials is aggregate (~80%), this assumption is felt to be reasonably valid. However, properly measuring the specific heat of geopolymer concrete would refine the accuracy of this energy analysis. The heat required to raise the geopolymer concrete from  $21^\circ \text{ C}$  to  $75^\circ \text{ C}$  is calculated as 102.8 MJ. The concrete must then be held at an elevated temperature for 24-48 hours. As with the activating solution production, heat losses from a well insulated oven wall were estimated at  $0.194 \text{ MJ m}^{-2} \text{ h}^{-1}$ . An oven slightly larger in volume than the concrete would show losses of  $2.6 \text{ MJ h}^{-1}$ . Thus, longer curing durations will require greater inputs of energy to maintain elevated temperatures for longer periods of time.

The energy use of each batch and curing group was calculated using the methodology described above. A comparison of the energy requirements for the three mix designs and six curing regimens is shown in Table 6. In studying these results it is clear that the bulk of the embodied energy in the geopolymer cement production is tied to the NaOH content. However, since compressive strength gains decreased with additions of NaOH in excess of 13% of the fly ash content, the other factors are very significant. In these experiments, the impact of 24 additional hours of high temperature curing was a 12% gain in compressive strength. The energy required for the additional curing is estimated at 62.6 MJ, which is a more efficient method of increasing the strength than adding alkalinity.

The highest strength concrete produced contained the materials of Mix #2 and was aged for 48 hours and cured for 48 hours. Specimens from this group had an average compressive strength of 67 MPa. As shown in the rightmost column of Table 6, the strength per MJ of energy input is calculated for all batches. The highest strength is associated with the lowest MJ/MPa designation. This demonstrates that optimizing the curing regimen is a more energy efficient and effective method of increasing the strength of geopolymer cement concrete than the addition of alkalinity. Thus, the 67 MPa batch is selected as the optimum concrete design. The energy required to develop the cementitious component of  $1 \text{ m}^3$  of this concrete is estimated at 1,501 MJ.

*Energy required to produce Portland cement concrete*

The Portland Cement Association (PCA) has published a lifecycle inventory of the energy and material inputs to concrete <sup>21</sup>. In this document the Portland cement products ready-mix concrete, precast concrete and concrete masonry units are analyzed. Due to the heating requirements of the geopolymer cement concrete presented in this paper that require it to be produced in a factory setting, it is most directly comparable to the 70 MPa precast concrete mix that is studied in the PCA document. The mix design for this concrete is shown in Table 7, below.

Table 6: Energy required to produce concrete of various strengths [MJ]

<i>Age Time [days]</i>	<i>Cure Time [hours]</i>	<i>f<sub>c</sub>' [MPa]</i>	<i>Produce NaOH</i>	<i>Heat Activator</i>	<i>Heat Concrete to 75° C</i>	<i>Maintain Concrete at 75° C</i>	<i>Total Energy</i>	<i>MJ/MPa</i>
0	24	36.6	1018.2	5.8	102.8	62.8	1189.7	32.5
0	24	50.7	1267.1	“	“	62.8	1438.5	28.4
0	24	32.5	1495.5	“	“	62.8	1667.0	51.4
0	48	41.4	1018.2	“	“	125.6	1252.5	30.2
0	48	55.0	1267.1	“	“	125.6	1501.4	27.3
0	48	43.7	1495.5	“	“	125.6	1729.8	39.6
24	24	40.8	1018.2	“	“	62.8	1189.7	29.2
24	24	53.3	1267.1	“	“	62.8	1438.5	27.0
24	24	42.5	1495.5	“	“	62.8	1667.0	39.2
24	48	44.6	1018.2	“	“	125.6	1252.5	28.1
24	48	64.2	1267.1	“	“	125.6	1501.4	23.4
24	48	46.7	1495.5	“	“	125.6	1729.8	37.0
48	24	40.9	1018.2	“	“	62.8	1189.7	29.1
48	24	57.1	1267.1	“	“	62.8	1438.5	25.2
48	24	54.6	1495.5	“	“	62.8	1667.0	30.5
48	48	48.1	1018.2	“	“	125.6	1252.5	26.0
48	48	67.5	1267.1	“	“	125.6	1501.4	22.2
48	48	55.8	1495.5	“	“	125.6	1729.8	31.0

Table 7: Mix design for 70 MPa concrete

<i>Raw Material</i>	<i>kg/m<sup>3</sup></i>
Cement	445
Silica Fume	56
Water	136
Coarse Aggregate	1,112
Fine Aggregate	611

In order to compare the energy requirement for manufacturing the two concretes, it is assumed that the primary differences in the production process are in the preparation of the cement and the necessity for elevated curing temperatures in the case of the geopolymer cement concrete. Thus, the other processes such as mixing, transporting, facility lighting and maintenance, etcetera, are similar. The embodied energy of Portland cement averaged over the many production methods is  $4.798 \text{ MJ kg}^{-1}$ <sup>22</sup>. In order to produce the 445 kg of cement required for  $1 \text{ m}^3$  of concrete, 2,131 MJ of energy would be required. As with the geopolymer cement concrete energy assessment, the energy used to collect the silica fume is not considered because it is required to be removed from the flue gas of an unrelated industrial process.

#### *Comparison of production energy of geopolymer and Portland cement concrete*

The difference in energy required to produce 70 Mpa Portland cement concrete and 67.5 Mpa geopolymer cement concrete is 630 MJ or 30%. The range of energy requirements for production of the concretes made in this study are shown in Figure 6. Also plotted is an estimate of the energy required to produce Portland cement concrete of various strengths. Other points along the Portland cement concrete curve are also taken from the Life cycle inventory of Portland cement concrete<sup>21</sup>. Figure 6 shows that the geopolymer cement concretes require less production energy than Portland cement concretes in concretes with higher compressive strength.

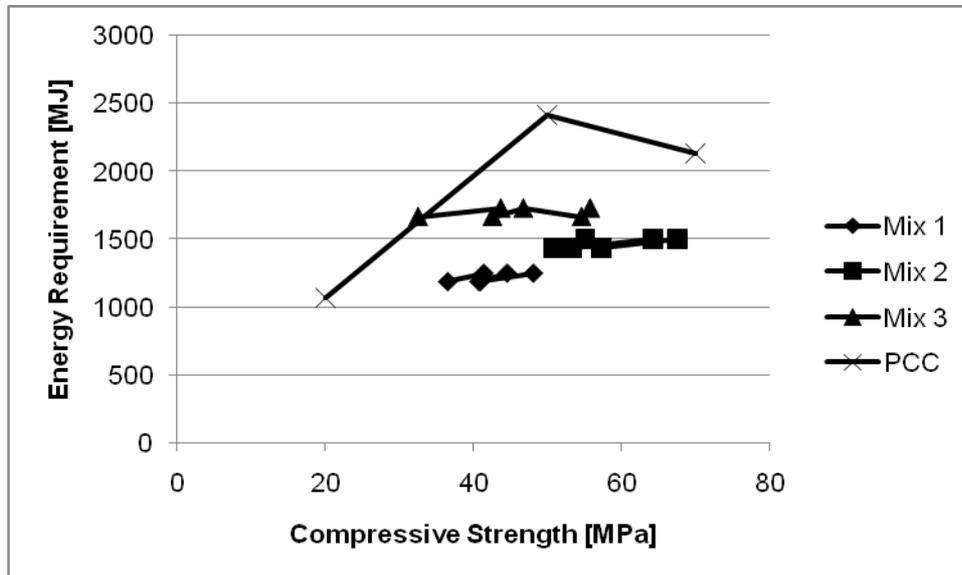


Figure 5: Comparison of energy inputs for various strength geopolymer and Portland cement concretes

## CONCLUSIONS

Three batches of geopolymer cement concrete were produced with activating solutions having different levels of alkalinity. Cylindrical specimens were created and allowed to age under ambient conditions for zero, one or two days. These were then cured at 75° C for either one or two days. The results of compression tests on these cylinders have shown that all three variables have an influence on strength development. The two concretes produced with lower alkalinity activating solutions benefited most from additional curing time. The concrete produced with a higher alkalinity activating solution benefited most from additional aging time.

Energy analyses indicate that geopolymer cement concrete can be produced with a smaller energy footprint than Portland cement concrete. This distinction is important relative to both the economics of production and the proportional relationship of energy use to greenhouse gas generation. Greenhouse gas emissions from Portland cement manufacture are sourced both from the carbon liberated from the cement source materials as well as the fuels used to heat the kiln. Producing geopolymer cement from fly ash eliminates both these greenhouse gas sources. Further, by diverting fly ashes from ponds and landfills, beneficial reuse eliminates the possibility of the negative environmental impacts associated with these storage techniques.

The energy savings of geopolymer cement concrete can be extended in several ways. Production of the alkalinity source is the most energy intensive feature of the concrete manufacture process. However, it may be possible to locate a source of alkalinity in the waste stream that can serve as a substitute. Further, curing temperatures that were

used in this study, as well as by other research groups, are within a range whereby they could be maintained by waste heat from another process. Work towards these two production developments would result in an extremely low-energy and low-emissions material.

## FURTHER RESEARCH

- As is seen in figures 1 and 2 it does not seem that the Mix #2 and Mix #3 specimens have completed their aging cycle and might have continued to gain in strength if an additional day were provided. Longer duration aging cycles should be investigated since this provides strength gains that do not require the input of additional energy.
- The energy analysis of the geopolymer production process could be made more accurate if specific heat of geopolymer concrete were known with greater certainty. Also of interest for improving the accuracy of this energy analysis would be the inclusion of transportation energy for materials used in both Portland cement concrete as well as geopolymer cement concrete.
- All batches studied for this paper were cured at 75° C. Lower temperatures might also be effective at producing high strength concretes and would also be more easily attainable from waste heat sources. Similar experiments should be attempted at lower curing temperatures.

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