University of Southern Queensland

Faculty of Health, Engineering and Sciences

Establishing a Mix Design Procedure for Geopolymer Concrete

A dissertation submitted by

Mr Aaron Paul Wilson

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ABSTRACT

There has been much research completed during recent years on the topic of geopolymer concrete. What has been missing is the combination of this research in a way that would allow use of geopolymer concrete as a replacement to concrete based on Ordinary Portland Cement. This dissertation addresses this requirement for a standard mix design for geopolymer concrete.

The research data was combined into a database and manipulated to give the ratios of sodium hydroxide solution to sodium silicate solution, alkaline liquid to fly ash or binder, water to geopolymer solids, superplasticizer to binder and also the molar weight of the sodium hydroxide solution.

These ratios were then input into Matlab, along with their measured compressive strength, to create artificial neural networks (ANNs). These ANNs learnt from the input data and output a compressive strength for each input line of data. This output value was obtained via set algorithms based on the input data.

It was then possible to select a mix design for standard grades of Geopolymer concrete. The Class F Fly Ash and Ground-granulated Blast-furnace Slag mixture was selected to test these outputs of the ANNs.

LIMITATIONS OF USE

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Aaron Paul Wilson
Student Number: 0050052015

Signature

22 October 2015
Date

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Nomenclature and Acronyms

ANN	-	Artificial Neural Networks
OPC	-	Ordinary Portland Cement
GPC	-	Geopolymer Concrete
CO_2	-	Carbon Dioxide
FA	-	Fly Ash
GGBFS	-	Ground-granulated Blast-furnace Slag
NaOH	-	Sodium Hydroxide
SP	-	Superplasticizer
MPa	-	Mega Pascals
kN	-	Kilo-Newtons
mm	-	Millimetres

CHAPTER 1 INTRODUCTION

1.1 Background

As the population of the world increases so too does the requirement for housing and development of infrastructure. Berkelmans and Wang (2012) estimated that 1.9 billion square metres of residential floor space was built in China alone in 2011. To put this into perspective in one year China built as much floor space as there is in all of Spain (nearly 2bn sq metres) (Economist, 2011).

It is also estimated that this growth will not peak until 2017 (Berkelmans, 2012), although others believe that this decline in construction will be short lived due to the underlying demand which is driven by higher salaries and increased urban population (Economist 2011).

This increased demand for housing, not only in China but world-wide, is feeding the global demand for building materials, in particular ordinary Portland cement (OPC) for the binder in concrete. Globally, we currently use approximately 2.8 billion tonnes of cement per annum and this is expected to increase to at least 4 billion tonnes per annum. For each tonne of cement produced, one tonne of carbon dioxide is released into our atmosphere (Radlinski, 2011). Suhendro (2014) estimates that this figure equates to 8-10% of the world's total Carbon Dioxide (CO_2) emissions.

The damage that this level of pollution is doing to the atmosphere is unsustainable and as such we need to create a substitute for OPC. This substitute comes in the form of Geopolymer Concrete (GPC).

GPC uses industry by-products as a substitute binder for OPC. There are many materials that can be used as this binder such as fly ash (FA), Ground-granulated Blast-furnace Slag (GGBFS) and even clay. Currently, millions of tonnes of these by-products are being disposed of into landfill, whilst OPC is being produced at the highest volumes recorded. With these pozzolanic materials and an Alkaline Activator we can partially or completely remove the need for OPC in concrete production.

Some companies such as Wagners in Toowoomba, are currently utilising GPC. Wagners' Earth Friendly Concrete (EFC) was used for the Global Change Institute building at University of Queensland in Brisbane. EFC is the only geopolymer concrete currently available for commercial purchase in Queensland (Glasby, 2012). Glasby (2012) goes on to mention that EFC was not only used for its carbon emission reduction but for its superior performance in comparison to OPC. The EFC was batched and mixed in Toowoomba and then transported to a casting yard in Brisbane where the precast elements were fabricated.

Figure 1-1 Production of Precast Concrete Products (Glasby 2012)

The use of GPC by Wagners is a great step towards a low carbon concrete industry, but the only way to truly reduce the reliance upon OPC is to make the mix design for GPC available to the public. It is understandable that companies as such do not want to release their intellectual property because there is a lot of time and money spent on research and development of these products. To simply release this information would not only reduce the monopoly that these companies have on the market, but would also hand their competitors free research that in some parts may have taken decades to perfect. This is an issue that needs to be solved before any such data would be available for public use and until then, OPC will continue to be used.

It is the hope of this report that a standard mix design for 32MPa GPC is made available for public use and as such incorporated into the Australian construction industry and subsequently global construction practices. It is through the use of a mix design, based on commonly available materials, that carbon emissions from the concrete industry can be reduced. However, due to the time limitations, more research will be required to complete the range of commonly available concrete grades.

1.2 Aims and Objectives

The overall aim of this project is to identify a suitable mix design for 32MPa GPC that can be used by anyone in Australia or even worldwide.

The research objectives are as follows:

1. Obtain GPC mix design data from available journals and publications, paying close attention to materials that can be easily obtained and are therefore more common.
2. From obtained data, identify trends for various strengths of concrete using Artificial Neural Network (ANN) Analysis through Matlab.
3. Refine data obtained from Matlab and produce mix design procedure for 32MPa GPC.
4. Test a chosen mix design for compressive strength.

1.3 Scope of Study

The scope of this study will identify a suitable mix design to be used for the creation of GPC.

Limitations of research include:

- Only available data will be collected, limiting the amount of refinement available for the mix design. As such the outcomes are mostly reliant on the work of others.
- Only a mix design procedure for 32MPa GPC will be found. This is a common grade of concrete used but not the only one. More research into all grades should be done to allow the use of GPC in all facets of the concrete industry.

- Mix design will be based on materials available in the research area, Toowoomba. This will be kept as close to national and international availability as possible but may need more research to incorporate materials available in lieu of the chosen materials.

1.4 Dissertation Outline

There are 7 chapters in this dissertation. A short outline for each chapter is detailed below.

Chapter 2 – Literature Review

The literature review is one of the most important parts of this dissertation. Without the data collected from existing publications it would be a gigantic task to trial different estimated mix designs and as such would be out of reach for the time frame of this study.

The literature review will:

- Establish the need for a substitute for concrete made with OPC by reporting the environmental effects of producing cement
- Provide existing means of producing GPC
- Define the materials required in the production of GPC
- Indicate the reaction of chemicals required to produce GPC
- Also denote the lack of available information for GPC and possible reasons for this.

Chapter 3 – Mix Proportions and Database

This chapter will discuss the mix proportions found in the literature review and define which of these are appropriate for use in Australia and globally.

It will also define the database collected and the characteristics required to produce comparable concrete as to that made with OPC.

These characteristics include but are not limited to:

- Aggregate size and distribution
- Alkaline solution used and ratio of nano silicate to sodium silicate
- Water/binder ratio
- Alkaline solution/fly ash ratio
- Alkaline solution/slag ratio
- Compressive strength

Chapter 4 – Artificial Neural Network Development

This chapter will show the ANNs developed for the GPC. It will also provide the output ratios of materials required for standard concrete grades.

Chapter 5 - Testing

This section will discuss the testing procedure for GPC based on existing industry standards. Items discussed will include but are not limited to:

- Materials used, their procurement and quantities required
- Procedure for mixing materials
- Required time for curing of concrete samples
- Testing devices used
- Compressive strength of samples

Chapter 6 – Results and Discussion

The results of the tests will then be defined and discussed in terms of use for industry in Australia and worldwide.

Chapter 7 – Conclusion

Chapter 7 recognizes the work completed in this dissertation in terms of filling the gaps found in literature regarding a mix design procedure for GPC. It will also compare existing mix designs found in the literature review. The results will then be summarized and defined for use in direct substitute for OPC concrete. Further research is recommended for better understanding of the conclusions made and to determine mix designs for other commonly used grades of concrete.

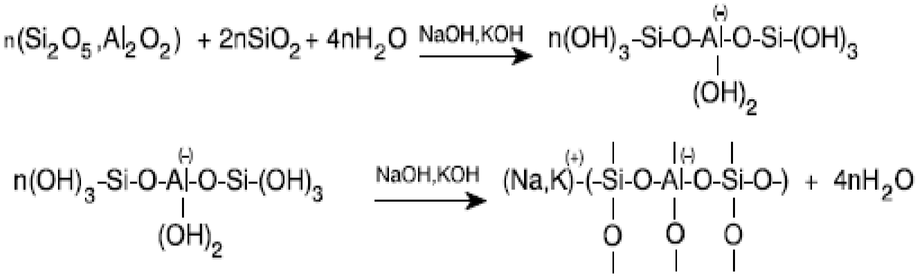
CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The purpose of this literature review is to identify the need for a suitable substitute for concrete made with OPC by reporting the environmental effects of producing cement. It will provide a background into current cement production, current GPC production methods and materials, cost comparisons to concrete made with OPC and also the chemical reactions required for GPC.

2.2 What is Geopolymer Concrete?

Geopolymer concrete (GPC) is a fairly new material in the construction industry. Geopolymers have been around since the 1950's but is wasn't until 1978 that the term geopolymer was invented by Joseph Davidovits (1994). Geopolymers are very similar to regular polymers in that they are transformed, they undergo polycondensation and set within minutes at low temperatures. Davidovits (1994) describes that in addition to the above, geopolymers are inorganic, hard, and able to withstand high temperatures due to their inflammable nature. GPC is made by mixing aluminosilicate oxides with inorganic alkali polysilicates to produce polymeric Silicate-Oxygen-Alkaline (Si-O-Al) bonds, the key chemical reactions required for the binding process.



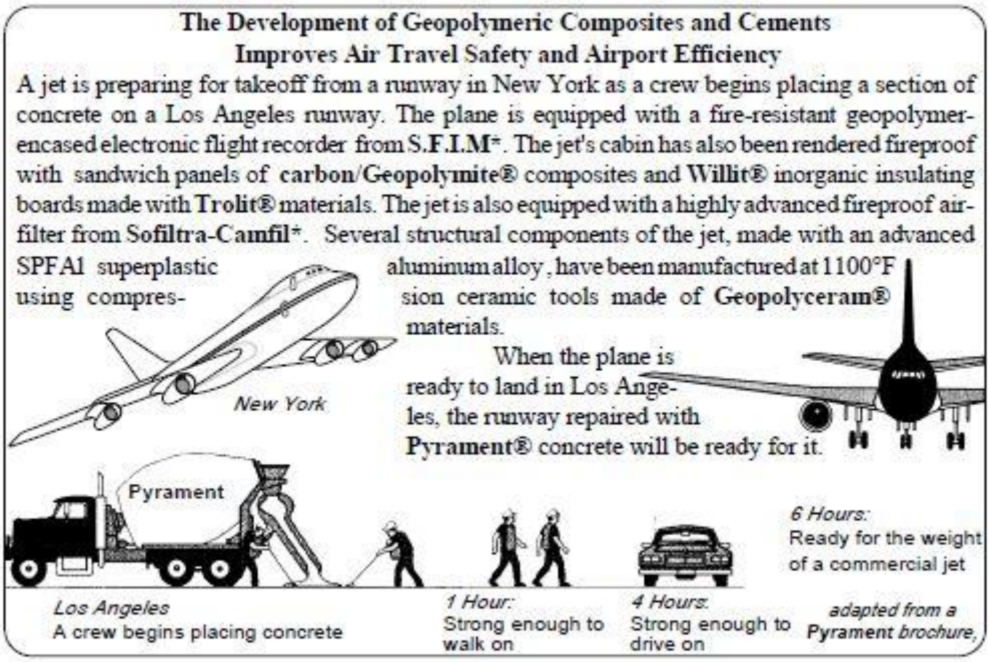
$$n(Si_2O_5,Al_2O_2) + 2nSiO_2 + 4nH_2O \xrightarrow{NaOH,KOH} n(OH)_3\text{-Si-O-}\overset{(-)}{\underset{\underset{(OH)_2}{|}}{Al}}\text{-O-Si-}(OH)_3$$

$$n(OH)_3\text{-Si-O-}\overset{(-)}{\underset{\underset{(OH)_2}{|}}{Al}}\text{-O-Si-}(OH)_3 \xrightarrow{NaOH,KOH} (Na,K)^{(+)}\text{-}(\text{-}\underset{\underset{|}{\underset{O}{|}}}{\overset{|}{Si}}\text{-O-}\underset{\underset{|}{\underset{O}{|}}}{\overset{|\,(-)}{Al}}\text{-O-}\underset{\underset{|}{\underset{O}{|}}}{\overset{|}{Si}}\text{-O-}) + 4nH_2O$$

Figure 2-1 Exothermic Geopolymerization Process Chemical Reaction (Davidovits 1994)

Figure 2-1 depicts the exothermic geopolymerization process. It is considered that the reaction is a result of still hypothetical monomers being polycondensated. It is noted that the use of water is still required, as is with OPC (Davidovits, 1994).

Geopolymers were initially desired for the fast setting time. Davidovits gives the example of a runway prepared with GPC. Within one hour the concrete is strong enough to be walked on, at 4 hours strong enough for vehicle loads and finally at 6 hours, the concrete runway is ready to sustain the weight of a commercial jet, as shown in Figure 2-2. It is in recent years that the desire for GPC has been more focused on the environmental impact of traditional cement production methods.



The Development of Geopolymeric Composites and Cements
Improves Air Travel Safety and Airport Efficiency

A jet is preparing for takeoff from a runway in New York as a crew begins placing a section of concrete on a Los Angeles runway. The plane is equipped with a fire-resistant geopolymer-encased electronic flight recorder from **S.F.I.M***. The jet's cabin has also been rendered fireproof with sandwich panels of **carbon/Geopolymite®** composites and **Willit®** inorganic insulating boards made with **Trolit®** materials. The jet is also equipped with a highly advanced fireproof air-filter from **Sofiltra-Camfil***. Several structural components of the jet, made with an advanced SPF Al superplastic aluminum alloy, have been manufactured at 1100°F using compression ceramic tools made of **Geopolyceram®** materials.

When the plane is ready to land in Los Angeles, the runway repaired with **Pyrament®** concrete will be ready for it.

Los Angeles
A crew begins placing concrete

1 Hour:
Strong enough to walk on

4 Hours:
Strong enough to drive on

6 Hours:
Ready for the weight of a commercial jet

adapted from a **Pyrament** *brochure,*

Figure 2-2 Early Setting Example (Davidovits, 1994)

2.3 Environmental Impact

With the global focus on greenhouse gas emission reduction it is understandable that construction methods and materials are scrutinised. It is estimated that worldwide concrete consumption is currently at $1m^3$ per person. This in turns marks concrete as the world's highest consumed building material (Turner and Collins, 2013). Estimates vary but it is assumed that nearly one tonne of CO_2 is emitted for every tonne of cement produced. This means, based on current global population estimates, that around 7 billion tonnes of CO_2 is released into our atmosphere (Radlinski, 2011). Suhendro (2014) estimates that this figure equates to 8-10% of the world's total CO_2 emissions.

The crushing and treatment of limestone, one key component of OPC, is the main cause for the greenhouse gasses created during production. The limestone and other quarried rocks are ground into fine particles, dried and fed into a large rotating kiln where the materials are heated from 70 to 800 ° Celsius (CCANZ 1989).

GPC on the other hand contains little to no OPC. Instead, it uses industry waste products such as Fly Ash and Ground-granulated Blast-furnace Slag along with Alkaline Activators to create the binder. It is through the use of these binder alternatives that a reduction in CO_2 emissions created by OPC production could be decreased by as much as 80% (Turner and Collins 2013). This reduction equates to approximately 5.6 billion tonnes of CO_2 not entering our atmosphere.

2.4 Fly Ash

Fly Ash (FA) is the by-product of coal fired power stations. It is commonly being used as a cost effective substitute for some of the OPC required for standard concrete mixes. It is the goal of GPC to effectively replace OPC entirely with binder alternatives. It is estimated that over a billion tonnes of FA is currently produced worldwide with a utilization rate of only 20% (Sumajouw and Rangan, 2006).

Fly Ash is gathered from coal fired power stations all over the world for use in concrete mixes. It is created after the coal is fed into a series of mills which reduce the coal into a fine powder. The powder is then combusted in a boiler to produce the steam required for generation of power. It is during this process that minerals within the coal bind together to form spheres of a glassy alumina-silicate nature. Micrographs of the spheres are shown in Figure 2-3 through a scanning electron microscope.

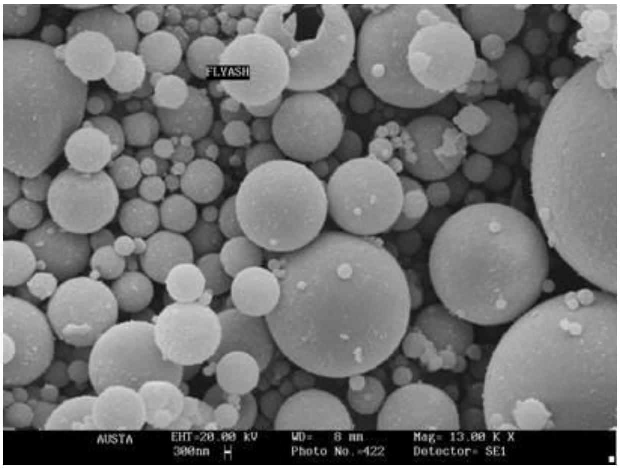


Figure 2-3 Glassy Fly Ash Spheres through Electron Microscope (Fly Ash Australia, 2010)

These spheres are collected by precipitation downstream of the boiler (Fly Ash Australia, 2010). Figure 2-4 illustrates the process described above.

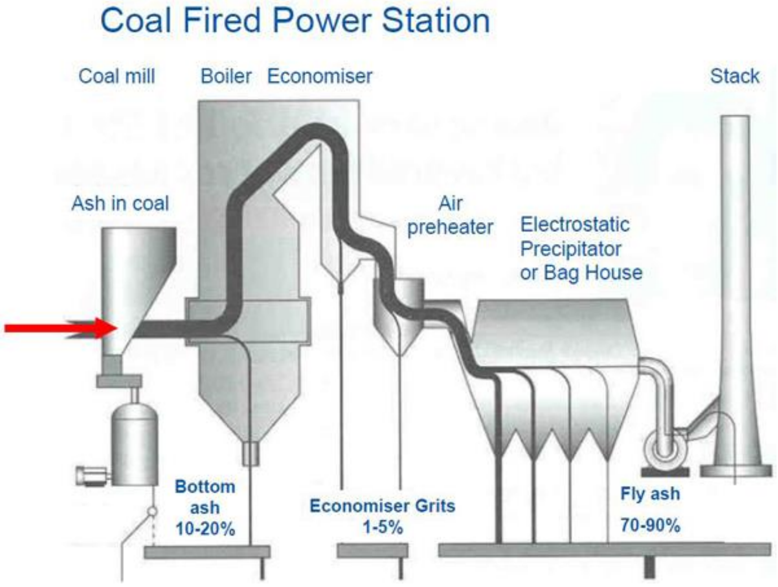


Figure 2-4 Fly Ash Retrieval Process (Fly Ash Australia, 2010)

There are two types of FA available worldwide, class C and class F. The calcium (CaO) content of FA is typically the greatest indicator for the behaviour of concrete. Generally, the higher the CaO content, the more FA is required to offset (Thomas, 2007). Wallah and Rangan (2006) stated that the use of higher calcium FA interferes with the polymerisation setting rate and alters the microstructure, therefore making it less desirable for use. Concrete Australia (2011) noted that class C was the least effective as it can cause early set if not blended with a retarder.

The classes are generally differentiated by the CaO content of the FA.

Table 2-1 denotes the different calcium percentages based on mass.

Table 2-1 Fly Ash Classes and CaO content (Thomas 2007)

Fly Ash Type	Calcium Content
Class F	< 8% CaO
Class C	>8% Cao

In most articles reviewed the amount of FA present in the mix was between 400-500 kg for every cubic metre of GPC (Hardjito 2005) (Lloyd and Rangan, 2010). This value decreases with the introduction of secondary binder material such GGBFS (Deb et al., 2014).

2.5 Ground-granulated Blast-furnace Slag

Ground-granulated Blast-furnace Slag (GGBFS) is another by-product of industry commonly used in the OPC concrete mix design. It is generally used to lower heat hydration, resist abrasion wearing from ground water or combat other adverse environmental conditions (Cement Australia, 2014). GGBFS is created during steel manufacturing when iron ore, coke and a flux are heated to melting point in a blast furnace. Upon completion of the smelting process, the remnants of the melting materials are collected and rapidly cooled. This melted material contains the lime in the flux and the aluminates and silicates of the ore and coke ash which have been chemically combined to form blast furnace slag. The slag is then cooled off and ground for use in concrete applications.

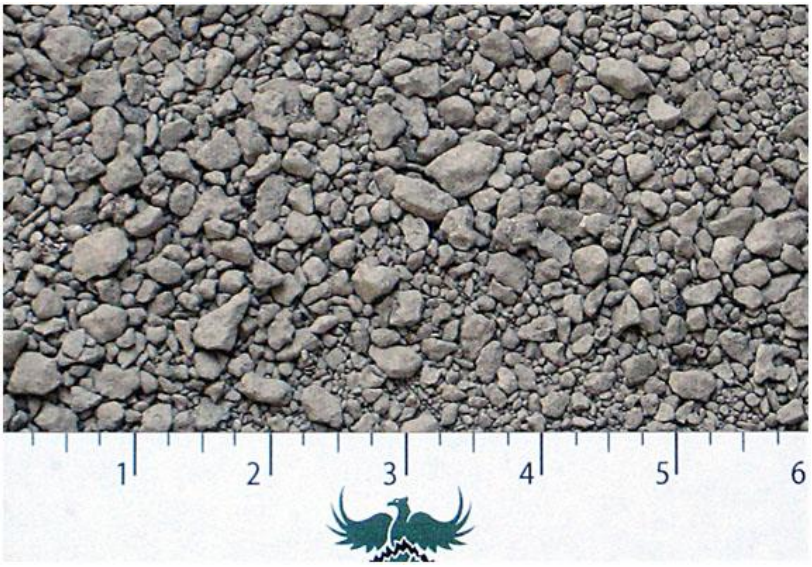


Figure 2-5 Blast Furnace Slag before grinding process (www.phxslag.com)

The typical quantities of GGBFS used in GPC production range from 10-80 kg for every cubic metre of GPC when combined with FA or up to 400 kg per cubic metre of GPC alone (Bernal et al., 2012) (Deb et al., 2014).

There are many alternative materials that can be used in the production of GPC such as kaolinite, palm oil and red mud. However, these materials are not as commonly available as FA and GGBFS and as such will not be considered for this study.

2.6 Alkaline Activators

The activators required to complete the polymerisation process are typically sodium silicate (SiO_2/Na_2O) and sodium hydroxide (NaOH) solutions. The higher the NaOH content the higher the resultant compressive strength (Hardjito, 2005). Potassium based hydroxide solutions are able to be used instead of the NaOH solutions but are generally ignored due to the higher associated costs, (Hardjito and Rangan, 2005).

From the literature reviewed the quantities of NaOH and SiO_2/Na_2O are as shown in the table below.

Table 2-2 Alkaline Activator Quantities

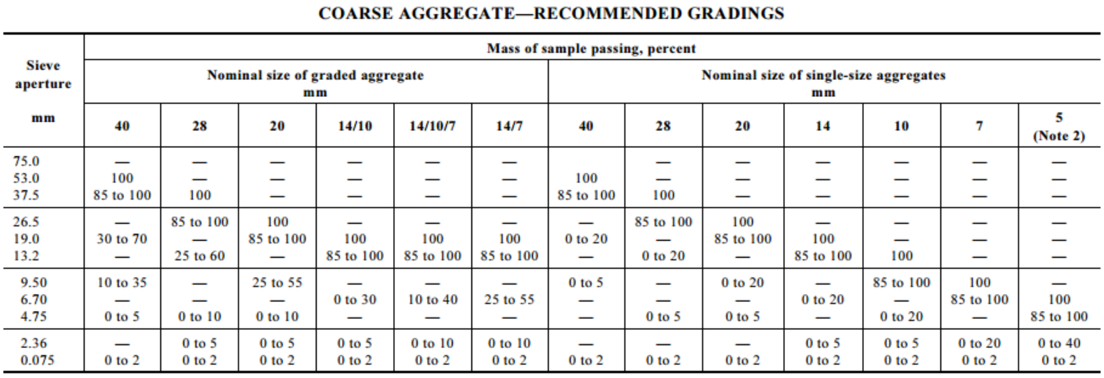
Activator Type	Content Range (kg/m^3 of GPC)	Average Content (kg/m^3 of GPC)
NaOH	0-170	53.3
SiO_2/Na_2O	0-256	110.5

Some of the data collected during the literature review indicated no NaOH or no SiO_2/Na_2O was used, these are extreme cases aimed at testing the limits of the materials. Out of 217 case study results, the average NaOH was 53.3 kg per m^3 of GPC and 110.5 kg per m^3 of GPC of SiO_2/Na_2O (M. Fareed Ahmed, 2011, Barber, 2010, Bernal et al., 2012, Chi, 2012, Chindaprasirt et al., 2007, Deb et al., 2014, Deevasan and Ranganath, 2011, Hardjito, 2005, Galvin and Lloyd, 2011, Hardjito et al., 2005, Joseph and Mathew, 2012, Talha Junaid et al., 2015, Kong and Sanjayan, 2010, Kusbiantoro et al., 2012, Lloyd and Rangan, 2010, Memon et al., 2011, Nath and Sarker, 2014, Olivia and Nikraz, 2011, Rahman and Sarker, 2011, Vora and Dave, 2013, Topark-Ngarm et al., 2014, T. Sujatha, 2012, Shi et al., 2012, Sumajouw and Rangan, 2006, Shojaei et al., 2015, Rangan, 2006, Xie and Ozbakkaloglu, 2015, Sarker et al., 2013).

2.7 Aggregates

Concrete Australia (2011) recommend that the aggregate content of GPC is that same as any other type of concrete with a blend consistent with the recommendations in AS2758.1 – 2014 as shown below.

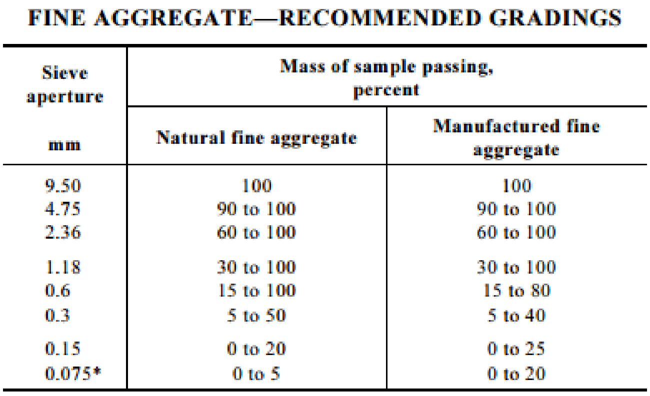
Table 2-3 Coarse Aggregate Gradings (Table B1 AS2758.1-2014)



COARSE AGGREGATE—RECOMMENDED GRADINGS

Sieve aperture mm	Mass of sample passing, percent												
	Nominal size of graded aggregate mm						Nominal size of single-size aggregates mm						
	40	28	20	14/10	14/10/7	14/7	40	28	20	14	10	7	5 (Note 2)
75.0	—	—	—	—	—	—		—	—	—	—	—	—
53.0	100	—	—	—	—	—	100	—	—	—	—	—	—
37.5	85 to 100	100	—	—	—	—	85 to 100	100	—	—	—	—	—
26.5	—	85 to 100	100	—	—	—	—	85 to 100	100	—	—	—	—
19.0	30 to 70	—	85 to 100	100	100	100	0 to 20	—	85 to 100	100	—	—	—
13.2	—	25 to 60	—	85 to 100	85 to 100	85 to 100	—	0 to 20	—	85 to 100	100	—	—
9.50	10 to 35	—	25 to 55	—	—	—	0 to 5	—	0 to 20	—	85 to 100	100	—
6.70	—	—	—	0 to 30	10 to 40	25 to 55	—	—	—	0 to 20	—	85 to 100	100
4.75	0 to 5	0 to 10	0 to 10	—	—	—	—	0 to 5	0 to 5	—	0 to 20	—	85 to 100
2.36	—	0 to 5	0 to 5	0 to 5	0 to 10	0 to 10	—	—	—	0 to 5	0 to 5	0 to 20	0 to 40
0.075	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2

Table 2-4 Fine Aggregate Gradings (Table B2 AS2758.1-2014)



FINE AGGREGATE—RECOMMENDED GRADINGS

Sieve aperture mm	Mass of sample passing, percent	
	Natural fine aggregate	Manufactured fine aggregate
9.50	100	100
4.75	90 to 100	90 to 100
2.36	60 to 100	60 to 100
1.18	30 to 100	30 to 100
0.6	15 to 100	15 to 80
0.3	5 to 50	5 to 40
0.15	0 to 20	0 to 25
0.075*	0 to 5	0 to 20

From the data collected, Hardjito (2005) displayed the most common blend of aggregates which are as follows.

Table 2-5 Typical Geopolymer Concrete Aggregate Blend

20mm (kg/m^3)	14mm (kg/m^3)	10mm (kg/m^3)	7mm (kg/m^3)	Fine Sand (kg/m^3)
277	370	0	647	554

Whereas, Kong and Sanjayan (2010) and Chindaprasirt et al. (2014) did not use any coarse aggregates. Kong and Sanjayan (2010) instead used a high volume of slag to compensate, and Chindaprasirt et al. (2014) used higher volumes FA and fine sand. Both resulted in comparable compression strengths.

Others used no 20mm or 14mm aggregates and instead made up the quanities using more 10mm, 7mm and Fine Sand. All total quantities of aggregates were approximately 1850kg per m^3 of GPC which is approximately 80% of the total weight (Deevasan and Ranganath 2011, Hardjito, D., et al. 2005, Olivia and Nikraz 2011, Bernal, Mejía de Gutiérrez et al. 2012, Chi 2012, Shojaei, Behfarnia et al. 2015, Deb, Nath et al. 2014, Nath and Sarker 2014, Topark-Ngarm, Chindaprasirt et al. 2014).

2.8 Super Plasticizer

Wallah and Rangan (2006) describes that super plasticizers (SP) were required to improve the workability of the fresh GPC concrete. As such, “a high-range water-reducing Naphthalene based super plasticizer was added to the mixture” (Wallah and Rangan 2006).

Wallah and Rangan (2006) added 6kg per m^3 of GPC to all of their mixes. This quantity was also similar to other research, with SP ranging from 6-12 kg per m^3 of GPC (Hardjito 2005, Hardjito, Wallah et al. 2005, Rangan 2006, Barber 2010, Kong and Sanjayan 2010, Lloyd and Rangan 2010, Galvin and Lloyd 2011, M. Fareed Ahmed 2011, Memon, Nuruddin et al. 2011, Olivia and Nikraz 2011, Rahman and Sarker 2011, Joseph and Mathew 2012, Kusbiantoro, Nuruddin et al. 2012, T. Sujatha 2012, Sarker, Haque et al. 2013, Vora and Dave 2013, Deb, Nath et al. 2014, Nath and Sarker 2014, Topark-Ngarm, Chindaprasirt et al. 2014, Shojaei, Behfarnia et al. 2015, Talha Junaid, Kayali et al. 2015, Xie and Ozbakkaloglu 2015).

Chindaprasirt, Chareerat et al. (2007) had quantities of SP ranging from 0-60 kg per m^3 of GPC, the higher quantities were used to compensate for the high calcium content of the class C FA used.

2.9 Compressive Strength Prediction

Recent studies have relied on the use of Artificial Neural Networks (ANN) to help predict compressive strength of GPC with different binding materials (Nazari and Torgal, 2012, Bondar, 2011). ANNs are described as a series of parallel architectures that work cooperatively to solve complex problems by connecting simple computing elements (Nazari and Torgal, 2012). The networks utilise learning capabilities obtained from example inputs, which make them perfect for use for the prediction of GPC compressive strength as available data is fairly limited.

An artificial neuron contains five main parts: inputs, weights, sum function, activation function and outputs (Topçu and Sarıdemir, 2008). The inputs are the known data collected from previous test results. Weights are values that demonstrate the effect that the input values have on the outputs. The effect of the weights is calculated by the sum function. The weighted sums of inputs are calculated by the following equation:

$$(\mathrm{net})_j = \sum_{i=1}^{n} w_{ij} x_i + b$$

Figure 2-6 Artificial Neural Network Weighted Sum Function (Topcu and Saridemir 2008)

where “$(\mathrm{net})_j$ is the weighted sum of the j. neuron for the input received from the preceding layer with n neurons, w_{ij} is the weight between the j. neuron in the preceding layer, xi is the output of the i. neuron in the preceding layer, b is a fix value as internal addition and Σ represents the sum function” (Topçu and Sarıdemir, 2008). The activation function is one which processes the net input obtained through the sum function and defines the output values. The output is created using a sigmoid function as follows

$$(\mathrm{out})_j = f(\mathrm{net})_j = \frac{1}{1 + \mathrm{e}^{-\alpha(\mathrm{net})_j}}$$

Figure 2-7 The Activation Function (Topcu and Saridemir 2008)

Where α is a constant used to control the slope of the semi-linear region (Topcu and Saridemir 2008).

In recent years, ANNs have been used in the civil engineering industry to overcome many problems such as determining structural damage, the modelling of material behaviour, and ground water monitoring (Topçu et al., 2008).

Topcu, Karakurt et al. (2008) used ANNs along with fuzzy logic to predict the strength development of GPC with different binding materials. They found that compressive strengths can be predicted through the use of ANNs in a short period of time with minimal error in comparison to test results.

Bondar (2011) concluded that the optimum network architecture to predict compressive strength of GPC was one with a three-layer feed forward network with tan-sigmoid function as the hidden layer transfer function and a linear function as the output layer.

Nazari and Torgal (2012) similarly concluded that the use of ANNs to predict the compressive strength of different GPC mixes was able to be done in a relatively short span of time with minimal error rates. They utilised a two-layer feed forward-back propagating network.

It was decided to use a three-layer feed forward network with a tan-sigmoid function as the hidden layer function, similar to that by Bondar (2011), in this study to predict the compressive strength of 32MPa GPC.

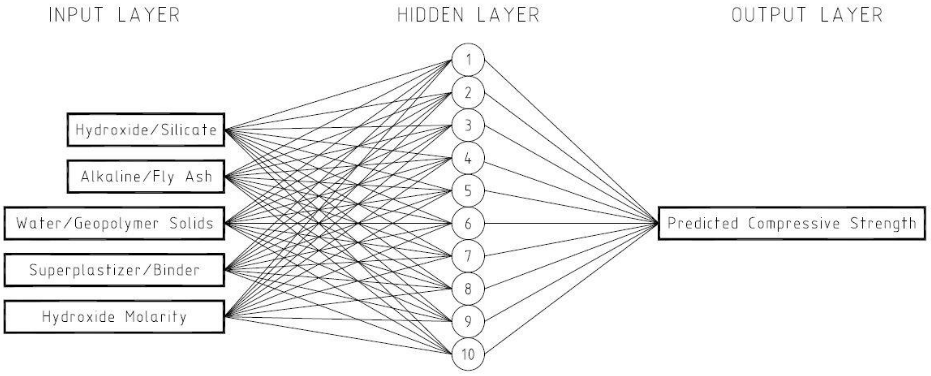


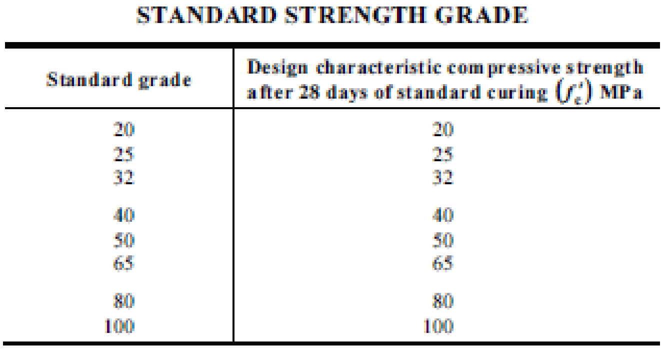
Figure 2-8 Class F Fly Ash Artificial Neural Network Diagram

CHAPTER 3 MIX PROPORTIONS AND DATABASE

3.1 Mix designs from collected works

As previously mentioned, many different materials and quantities were used in the reviewed literature. The following sections show the impact of these differences on the compressive strength of the Geopolymer Concrete (GPC). The compressive strength of the database entries were separated into groups that reflected a 28 day compression test result equal to or below the grade above in accordance with table 1 from AS 1379-2007, as shown below.

Table 3-1 Standard Strength Grades (AS1379-2007)



STANDARD STRENGTH GRADE

Standard grade	Design characteristic compressive strength after 28 days of standard curing (f'_c) MPa
20	20
25	25
32	32
40	40
50	50
65	65
80	80
100	100

According to Talha Junaid, Kayali et al. (2015), the key components that depict the strength of the GPC mix are as follows:

- Water to geopolymer solid ratio (W/GPS)
- Alkaline liquid to Fly Ash ratio (AL/FA)
- Strength increases with time and temperature
- Dry curing results in higher strengths than wet curing
- Higher silicates to hydroxide ratios result in higher strength
- Ratio of SiO_2/Na_2O in sodium silicate solution should be approximately 2.

3.1.1 Water to Geopolymer Solid Ratio

The water to geopolymer solid ratio (W/GPS) is the total mass of water in the system, including that used in the alkaline solution and extra water, divided by the total mass of the Fly Ash, Ground-granulated Blast-furnace Slag (GGBFS), sodium hydroxide pellets/flakes and sodium silicate solids (Ferdous et al., 2015). This ratio works in the same fashion as the water/cement ratio in OPC.

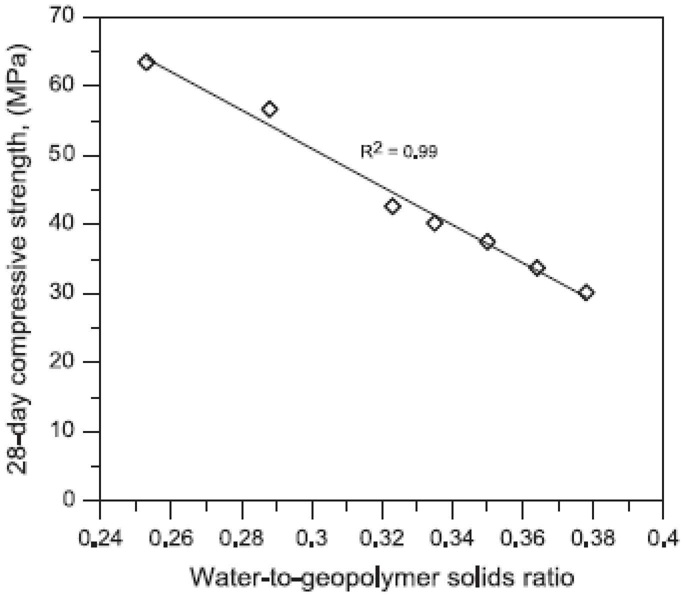
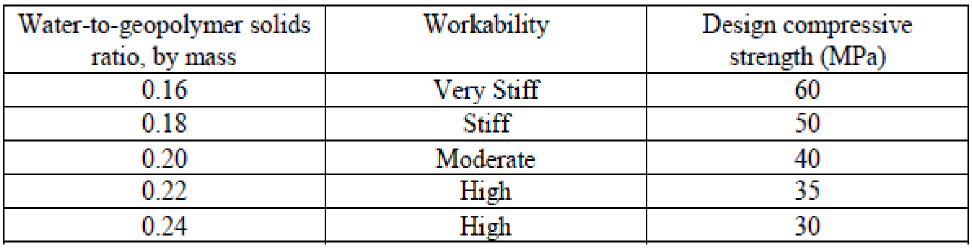


Figure 3-1 Compressive Strength to Water/Geopolymer Solids Ratio (Ferdous, Manalo et al. 2015)

As shown in Figure 3-1**Error! Reference source not found.**, the W/GPS atio has a direct effect on the strength of the concrete. The lower W/GPS results in higher strength concrete but is difficult to work with due to the dryness of the mix (Ferdous, Manalo et al. 2015). Based on **Error! Reference ource not found.**, the W/GPS ratio for 32MPa concrete is approximately 0.37. Lloyd, N. A. and B. V. Rangan (2010) indicated that the W/GPS ratio need not be this high to achieve 32MPa concrete. As shown in Table 3-2, the W/GPS ratio should be approximately 0.23. This would result in a highly workable mix based on 400kg of FA per cubic metre of GPC. The values given are dependent on the notion that all aggregates are in the saturated surface dry condition.

Table 3-2 Water to Geopolymer Solid Ratio (Lloyd, N. A. and B. V. Rangan 2010)



Water-to-geopolymer solids ratio, by mass	Workability	Design compressive strength (MPa)
0.16	Very Stiff	60
0.18	Stiff	50
0.20	Moderate	40
0.22	High	35
0.24	High	30

3.1.2 Alkaline Liquid to Fly Ash Ratio

The Alkaline liquid to Fly Ash ratio (AL/FA) depicts the total amount of sodium hydroxide and sodium silicate solutions that are required for geopolymerization of the FA. Lloyd, N. A. and B. V. Rangan (2010) recommend a range of 0.3-0.45 by mass. Talha Junaid, Kayali et al. (2015) expand this notion to depict how much hydroxide solution and silicate solution is required, as shown below.

$$\frac{\text{silicate solution}}{\text{hydroxite solution}} = 2.5$$

Figure 3-2 Hydroxide and Silicate Solution ratio (Talha Junaid, Kayali et al. 2015)

This equation indicates that approximately 2.5 times the quantity of hydroxide solution is required for the silicate part of the alkaline liquid. Talha Junaid, Kayali et al. (2015) indicated that the AL/FA ratio is linear with respect to the 7 day strength. A mix with 12M Sodium Hydroxide (NaOH) solution was cured for 24 hours at 80 ° C with the results shown in Figure 3-3.

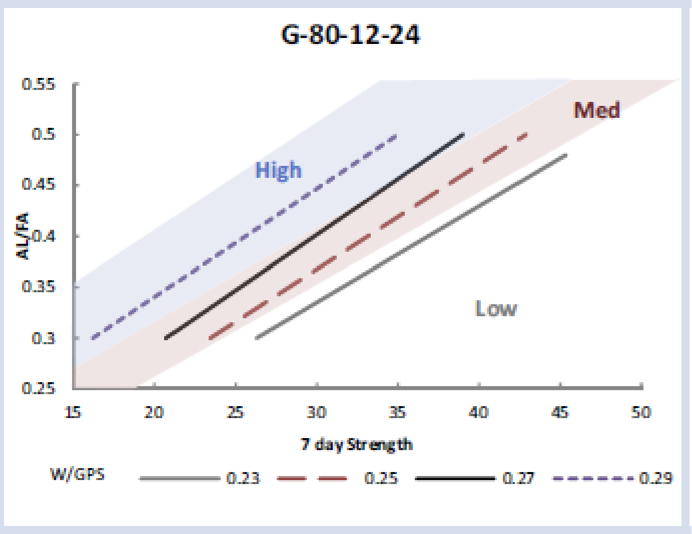


Figure 3-3 Alkaline/Fly Ash Vs 7 Day Strength for 12M Sodium Hydroxide Solution after 24 hours curing (Talha Junaid, Kayali et al. 2015)

Based on 32MPa concrete for medium workability and a W/GPS ratio of 0.27, the graph above would indicate an AL/FA ratio of approximately 0.4 which corresponds to the research by Lloyd, N. A. and B. V. Rangan (2010). This value is also used by Shojaei, M., et al. (2015) for the AL/GGBFS ratio. For this report the value of 0.4 will be the desired ratio for all mixes whether they be based on FA only, Ground-granulated Blast-furnace Slag (GGBFS) only, or a combination of FA and GGBFS.

3.1.3 Mix Design Database

After the literature review was complete, a database was established from a number of published articles based on the following criterion:

1. Only FA and GGBFS mixes would be included
2. A mix design could only be included once, duplicates from same authors were excluded
3. Extreme or out-of-the-ordinary mixes were excluded

As previously established, only FA and GGBFS mixes would be used as these materials are readily available in the Australian construction industry. Mixes containing other materials were not included due to ease of access and therefore cost.

Many authors re-used mix designs for different research purposes such as acid resistance, fire resistance, etc. Each mix still gave the same compressive strength. As such a mix design could only be included once.

Some authors used extremely high percentages of materials to test the impact on the overall mix. These mixes were excluded as they did not represent typical construction purposes.

3.1.4 Class F Fly Ash Concrete Mix Design from database

The data shown in this section is a portion of the database for GPC based on class F Fly Ash. For formatting reasons, the entire table is too large to fit within this section and can therefore be found in Appendix B: Database.

The key ratios for the establishment of the mix design are:

- Hydroxide/Silicate
- Alkaline/Fly Ash
- Water/Geopolymer Solids

The mixes contain no OPC or GGBFS. For the purposes of this report only the grades N20, N25, N32 and N40 will be shown (Wallah and Rangan 2006, Hardjito 2005, Hardjito, Wallah et al. 2005, Rangan 2006, Barber 2010, Lloyd and Rangan 2010, Galvin and Lloyd 2011, M. Fareed Ahmed 2011, Olivia and Nikraz 2011, Rahman and Sarker 2011, Joseph and Mathew 2012, Kusbiantoro, Nuruddin et al. 2012, T. Sujatha 2012, Sarker, Haque et al. 2013, Vora and Dave 2013, Deb, Nath et al. 2014, Nath and Sarker 2014, Sumajouw, M. D. J. and B. V. Rangan 2006, Xie and Ozbakkaloglu 2015).

Table 3-3 Class F Fly Ash Mix Design from database

Grade	Fly Ash/Tot Weight	Coarse Agg/Tot Weight	Sand/Tot Weight	Hydroxide/ Silicate	AL/FA	W/GPS	f'c (MPa)
N20	0.142857	0.489796	0.263265	0.40	0.41	0.297	20
N20	0.155102	0.43	0.33	0.36	0.39	0.188	24
N20	0.174694	0.477551	0.257143	0.50	0.40	0.295	24
N25	0.163265	0.498776	0.268571	0.40	0.35	0.180	25
N25	0.163265	0.498776	0.268571	0.67	0.35	0.180	27
N25	0.174694	0.477551	0.257143	0.40	0.40	0.251	29
N25	0.174694	0.477551	0.257143	0.40	0.40	0.251	30
N32	0.166531	0.528163	0.226122	0.40	0.35	0.220	32
N32	0.174694	0.477551	0.257143	0.40	0.40	0.251	32
N32	0.174694	0.477551	0.257143	0.50	0.40	0.253	32
N32	0.166531	0.528163	0.226122	0.40	0.35	0.197	35
N32	0.174694	0.477551	0.257143	0.50	0.40	0.253	35
N32	0.166894	0.480408	0.254286	0.67	0.35	0.226	35.73
N32	0.166531	0.528163	0.226122	0.50	0.38	0.221	36

N32	0.166531	0.528163	0.226122	0.40	0.35	0.228	36
N32	0.165714	0.487347	0.262449	0.40	0.35	0.232	37
N32	0.164898	0.485714	0.261224	0.40	0.35	0.230	37
N32	0.195918	0.470612	0.24449	0.50	0.35	0.217	37.09
N32	0.166531	0.490204	0.264082	0.40	0.35	0.205	38
N32	0.181404	0.480408	0.254286	0.40	0.35	0.211	38.69
N40	0.166531	0.490204	0.264082	0.40	0.35	0.219	40
N40	0.166531	0.528163	0.226122	0.40	0.35	0.210	40
N40	0.166531	0.528163	0.226122	0.50	0.38	0.221	42
N40	0.166531	0.490204	0.264082	0.40	0.35	0.205	42
N40	0.188384	0.480408	0.254286	0.50	0.30	0.188	42.51
N40	0.166531	0.528163	0.226122	0.40	0.35	0.175	44
N40	0.166531	0.490204	0.264082	0.40	0.35	0.190	45
N40	0.166531	0.490204	0.264082	0.40	0.35	0.175	47
N40	0.163265	0.39	0.35	0.40	0.50	0.328	47.99
N40	0.194286	0.528163	0.226122	2.50	0.35	0.180	48
N40	0.166531	0.490204	0.264082	0.66	0.42	0.220	48
N40	0.155102	0.503265	0.220408	0.40	0.52	0.230	49

As noted from Table 3-3, the W/GPS ratio generally decreases as the compressive strength increases, which corresponds to Chapter 3.1.1. The AL/FA ratio is typically within the range of 0.3-0.45 as denoted in Chapter 3.1.2. The Fly Ash/Total Weight, Coarse Agg/Total Weight and Sand/Total weight are based on a concrete density of 2400kg/m^3. This may not be entirely accurate as the weight of the materials and water may be more or less than this figure. It is recommended that these ratios be taken as an estimate.

3.1.5 Class C Fly Ash Concrete Mix Design from database

The data shown in this section is a portion of the database for GPC based on class C Fly Ash, see Appendix B: Database for the full database. The mixes contain no OPC or GGBFS. For the purposes of this report only the grades N25, N32 and N40 will be shown (Chindaprasirt, P., et al. 2007, Topark-Ngarm, P., et al. 2014).

Table 3-4 Class C Fly Ash Mix Design from database

Grade	Fly Ash/Tot Weight	Coarse Agg/Tot Weight	Sand/Tot Weight	Hydroxide/ Silicate	AL/FA	W/GPS	f'c (MPa)
N25	0.21	0.00	0.56	0.49	0.51	0.295	26
N25	0.21	0.00	0.56	1.00	0.51	0.293	30
N32	0.21	0.00	0.56	0.50	0.51	0.295	32
N32	0.17	0.45	0.24	0.50	0.50	0.222	33.8
N32	0.21	0.00	0.56	0.49	0.51	0.239	36
N32	0.17	0.45	0.24	1.00	0.50	0.229	37.64
N32	0.21	0.00	0.56	0.49	0.51	0.267	38
N32	0.17	0.45	0.24	0.50	0.50	0.222	39.02
N40	0.17	0.45	0.24	1.00	0.50	0.229	39.67
N40	0.21	0.00	0.56	2.00	0.51	0.272	40
N40	0.21	0.00	0.56	2.00	0.51	0.300	42
N40	0.21	0.00	0.56	0.50	0.51	0.267	43
N40	0.21	0.00	0.56	1.00	0.51	0.265	45
N40	0.17	0.45	0.24	1.00	0.50	0.229	45.34
N40	0.17	0.45	0.24	0.50	0.50	0.222	46.69
N40	0.21	0.00	0.56	1.00	0.51	0.237	48
N40	0.21	0.00	0.56	2.00	0.51	0.254	48

As noted in Table 3-4, there are many differences in comparison to the Class F mix design database. These differences are as follows

- Hydroxide/Silicate ratios are much higher for Class C FA
- AL/FA ratios are much higher for Class C FA
- W/GPS is also higher for Class C FA

This coincides with that denoted in Chapter 2.4 and would explain why the cost of working with Class C FA would be greater than that found with Class F FA.

3.1.6 Class F Fly Ash and Ground-granulated Blast-furnace Slag Concrete Mix Design from database

The data shown in this section is a portion of the database for GPC based on class F FA and GGBFS from the database, see Appendix B: Database for the full database. The mixes contain no OPC. For the purposes of this report only the grades N25, N32 and N40 will be shown (Deb, P. S., et al. 2014, Nath, P. and P. K. Sarker 2014, Kusbiantoro, A., et al. 2012, Kong, D. L. Y. and J. G. Sanjayan 2010).

Table 3-5 Class F Fly Ash and Ground-granulated Blast-furnace Slag Concrete Mix Design from database

Grade	FA/ Tot Weight	Slag/ Tot Weight	Coarse Agg/Tot Weight	Sand/Tot Weight	Hydroxide/ Silicate	AL/ FA	AL/ Slag	AL/ binder	W/ GPS	f'c (MPa)
N25	0.15	0.02	0.50	0.27	0.40	0.39	3.50	0.35	0.20	27
N25	0.15	0.02	0.50	0.27	0.67	0.39	3.50	0.35	0.20	27
N25	0.15	0.02	0.49	0.27	0.40	0.50	4.50	0.45	0.22	30
N32	0.14	0.00	0.49	0.26	0.40	0.42	13.7	0.41	0.30	32
N32	0.15	0.02	0.49	0.27	0.40	0.44	4.00	0.40	0.20	33
N32	0.15	0.02	0.49	0.27	0.50	0.44	4.00	0.40	0.20	34
N32	0.15	0.02	0.49	0.27	0.67	0.44	4.00	0.40	0.19	35
N32	0.13	0.03	0.50	0.27	0.40	0.44	1.75	0.35	0.20	35
N32	0.16	0.03	0.53	0.22	0.00	0.29	1.29	0.23	0.21	35
N32	0.13	0.01	0.49	0.26	0.40	0.44	5.88	0.41	0.30	38
N40	0.15	0.02	0.49	0.27	0.40	0.44	4.00	0.40	0.20	40
N40	0.15	0.02	0.49	0.27	0.67	0.44	4.00	0.40	0.20	43
N40	0.15	0.02	0.49	0.27	0.40	0.39	3.50	0.35	0.17	44
N40	0.13	0.03	0.50	0.27	0.67	0.44	1.75	0.35	0.20	45
N40	0.13	0.03	0.49	0.27	0.40	0.50	2.00	0.40	0.20	45
N40	0.13	0.03	0.49	0.27	0.40	0.50	2.00	0.40	0.20	47
N40	0.07	0.14	0.00	0.63	0.40	0.91	0.41	0.28	0.14	48.6

The W/GPS ratio, shown in Table 3-5, is fairly consistent for all grades of GPC. This is different to that shown for Class F FA in Table 3-3.

The AL/binder ratio is within the range of 0.3-0.45 as denoted in Chapter 3.1.2 and the Hydroxide/Silicate ratio is fairly similar to that in Table 3-3.

3.1.7 Ground-granulated Blast-furnace Slag Concrete Mix Design from database

The data shown in this section is a portion of the database for GPC based on GGBFS, see Appendix B: Database for the full database. The mixes contain no FA (Bernal, S. A., et al. 2012, Shojaei, M., et al. 2015, Chi, M. 2012).

Table 3-6 Concrete Mix Design from database for Ground-granulated Blast-furnace Slag

Grade	Slag/Tot Weight	Coarse Agg/Tot Weight	Sand/Tot Weight	Hydroxide/ Silicate	AL/Slag	W/GPS	f'c (MPa)
N20	0.16	0.35	0.35	3.00	0.28	0.49	22
N32	0.16	0.34	0.34	1.00	0.38	0.49	35
N32	0.16	0.50	0.25	5.00	0.40	0.33	38.1
N40	0.17	0.44	0.23	0.28	0.14	0.55	40
N40	0.17	0.44	0.23	0.28	0.18	0.56	46
N40	0.17	0.44	0.23	0.28	0.21	0.56	48

It is noticed from Table 3-6 that the W/GPS ratio increases as the compressive strength increases, which is opposite to that for the mix design for Class F FA and GGBFS. The AL/Slag ratio is also typically less than that shown in Chapter 3.1.2.

This would suggest that a mix design for GPC based on GGBFS without FA would behave differently to that found with Class F FA based GPC.

CHAPTER 4 ARTIFICIAL NEURAL NETWORK DEVELOPMENT

As previously mentioned, the study will use Artificial Neural Networks (ANN) to ascertain an optimum mix design for 32MPa Geopolymer Concrete (GPC). It was decided to create ANNs for all available mix design options for Fly Ash (FA) and Ground-granulated Blast-furnace Slag (GGBFS) for comparison of the mix designs and give the option to use either mix of materials.

To create the networks, the following inputs were taken from the database and fed into the neural network toolbox in Matlab.

1. Hydroxide /Sodium Silicate ratio
2. Alkaline Liquid/Fly Ash Ratio or Alkaline Liquid/Binder Ratio
3. Water/Geopolymer Solids
4. The Molarity of the Hydroxide solution
5. Superplasticizers/binder ratio

As mentioned in Chapter 2.9, it was decided to use a three-layer feed forward network with a tan-sigmoid function as the hidden layer function in this study to predict the compressive strength of 32MPa GPC.

Once the input and target data were arranged and entered into Matlab the ANNs were then able to be created. This was done by using the Matlab NNTOOL function. The NN toolbox allows you to enter data, train it and also simulate it, as well as many other functions which are not the focus of this project.

Bondar (2011) describes the feed forward and back propagation method as, for every interval, an output compressive strength is calculated from the current weights and biases based on the input data. Then for the second step, the weights and biases are modified by the back propagation algorithm. The performance function, mean square error in this case, are also minimised by this change of weights and biases in each step.

The training algorithm used in this project is the traingda algorithm, as offered in the NN toolbox. Bondar (2011) showed that the traingda algorithm stops training the data if any of the following conditions are met:

- The maximum repetitions or epochs are met
- The maximum timeframe has expired
- The performance is minimised to suit the target data
- The gradient of performance falls below min_grad

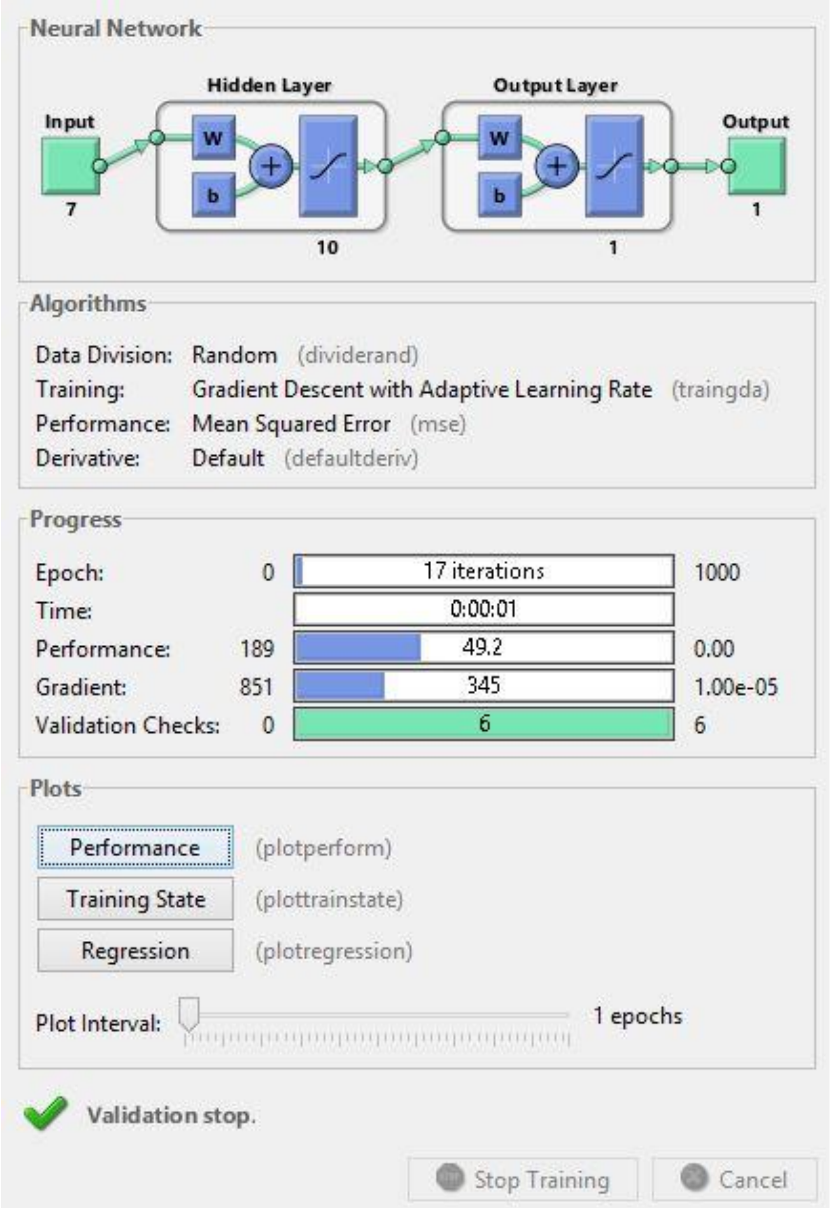
The training performances and outputs for the ANNs are shown in the following sections.

4.1 Class F Fly Ash and Ground-granulated Blast-furnace Slag Artificial Neural Network

The ANN was created based on Class F Fly Ash (FA) and Ground-granulated Blast-furnace Slag (GGBFS) as the binding material input presented in Table 3-5 and Appendix B: Database. As shown in Table 4-1, this network had 7 inputs and 1 output, being the compressive strengths.

Table 4-1 Class F Fly Ash and Ground-granulated Blast-furnace Slag Artificial Neural Network Inputs and Predicted Outputs

NaOH/ Sodium Silicate	AL/FA	AL/Slag	AL/Binder	W/GPS	Super/ Binder	NaOH Molarity	Actual Comp. Strength (MPa)	Predicted Comp. Strength (MPa)
0.40	0.44	5.88	0.41	0.30	0	8	15	31.45674
0.40	0.42	13.71	0.41	0.30	0	8	18	26.20466
0.40	0.39	3.50	0.35	0.20	0.015	14	27	30.10456
0.67	0.39	3.50	0.35	0.20	0.015	14	27	24.92903
0.40	0.50	4.50	0.45	0.22	0	12	30	32.28533
0.40	0.42	13.71	0.41	0.30	0	8	32	26.20466
0.40	0.44	4.00	0.40	0.20	0	12	33	32.98397
0.50	0.44	4.00	0.40	0.20	0	12	34	31.15133
0.67	0.44	4.00	0.40	0.19	0	12	35	30.55009
0.40	0.44	1.75	0.35	0.20	0.015	14	35	28.77511
0.00	0.29	1.29	0.23	0.21	0	12	35	40.98999
0.40	0.44	5.88	0.41	0.30	0	8	38	31.45674
0.40	0.44	4.00	0.40	0.20	0	14	40	43.13738
0.67	0.44	4.00	0.40	0.20	0	14	43	39.28931
0.40	0.39	3.50	0.35	0.17	0	12	44	35.40669
0.67	0.44	1.75	0.35	0.20	0.015	14	45	25.59835
0.40	0.50	2.00	0.40	0.20	0	12	45	31.07638
0.40	0.50	2.00	0.40	0.20	0	14	47	41.65267
0.40	0.91	0.41	0.28	0.14	0	8	48.6	44.11854
0.40	0.92	0.42	0.29	0.14	0	8	52.8	43.82771
0.67	0.50	2.00	0.40	0.20	0	14	54	39.70501
0.40	0.92	0.42	0.29	0.14	0	8	54	43.82771
0.40	0.57	1.33	0.40	0.20	0	12	55	30.99393
0.40	1.36	0.62	0.42	0.20	0	8	55.4	49.46125
0.40	0.33	0.12	0.09	0.05	0	12	61.8	55.15615



Algorithms

Data Division: Random (dividerand)
Training: Gradient Descent with Adaptive Learning Rate (traingda)
Performance: Mean Squared Error (mse)
Derivative: Default (defaultderiv)

Progress

Epoch:	0	17 iterations	1000
Time:		0:00:01	
Performance:	189	49.2	0.00
Gradient:	851	345	1.00e-05
Validation Checks:	0	6	6

Plot Interval: 1 epochs

✓ Validation stop.

Figure 4-1 Class F Fly Ash and Ground-granulated Blast-furnace Slag Artificial Neural Network - Training Results

The selected algorithms used for the Class F FA and GGBFS ANN are shown at the top of Figure 4-1. At the end of the training:

- 17 epochs out of a maximum 1000 were used
- The time taken was 0:00:01.
- Performance was 49.2 out of 189
- The gradient was 345
- And 6 validation checks were performed

Figure 4-1 indicates that the validation checks were the reason why the training was stopped.

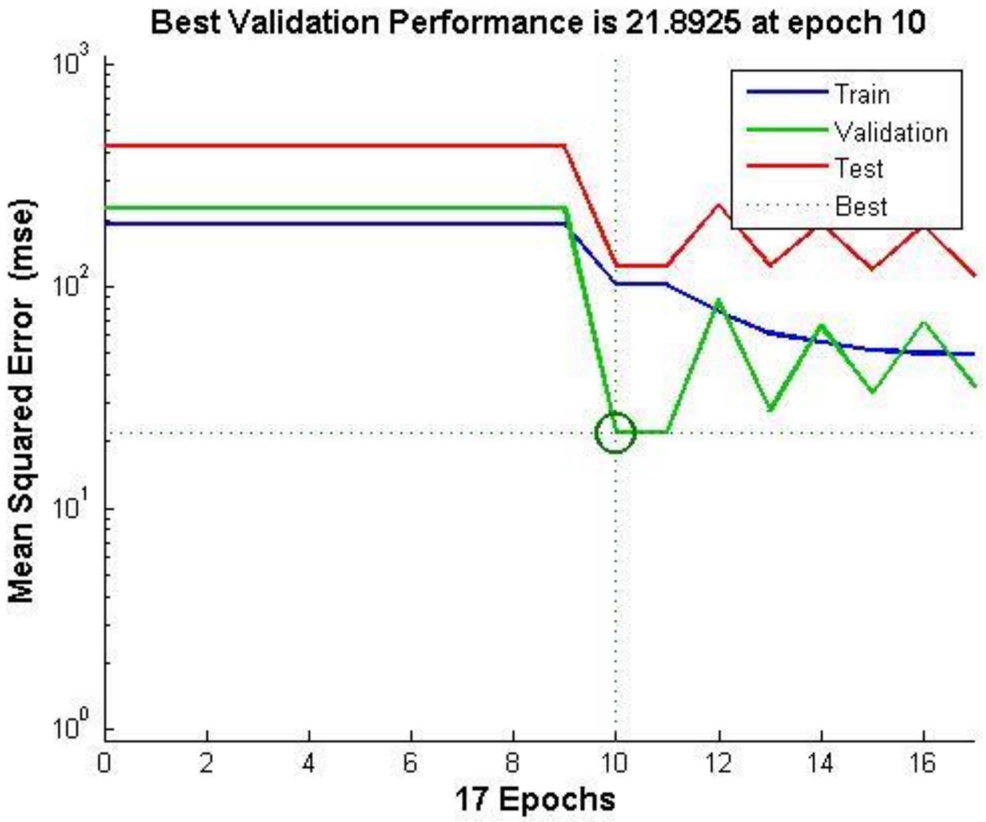


Figure 4-2 - Class F Fly Ash and Ground-granulated Blast-furnace Slag Artificial Neural Network - Training Performance Plot

As shown in Figure 4-2, the performance of the training was best at epoch 10 with the best validation being 21.8925.

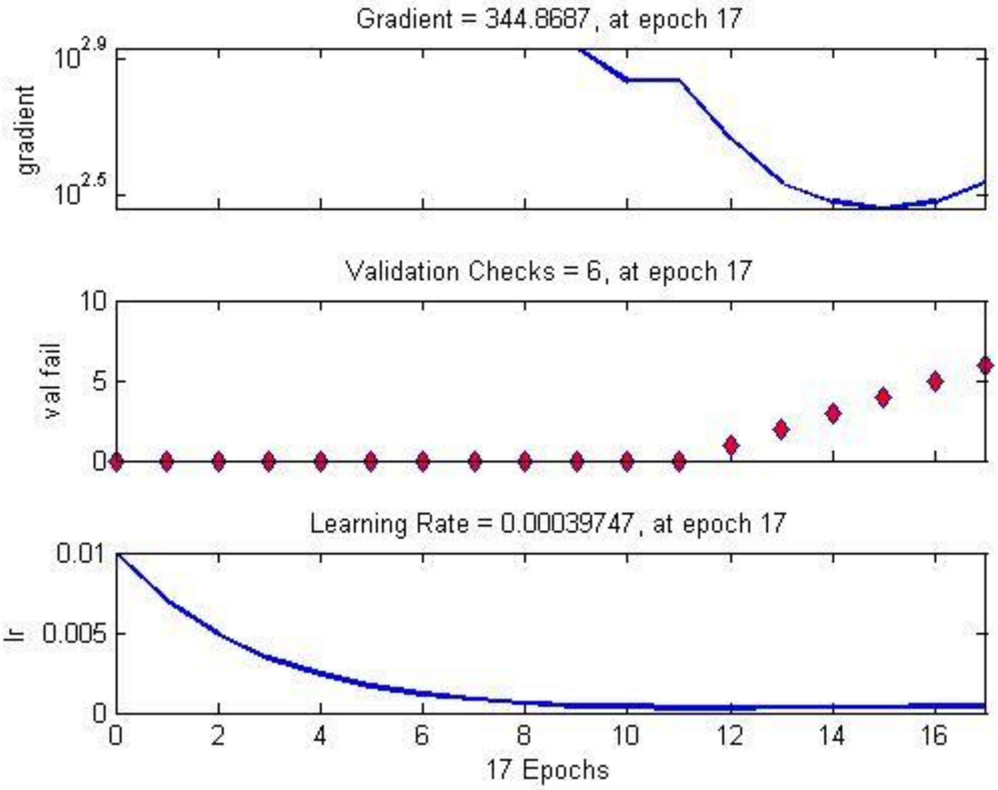


Figure 4-3 - Class F Fly Ash and Ground-granulated Blast-furnace Slag Artificial Neural Network - Training State Plot

The plots shown in Figure 4-3 form the training state plot. It shows the pattern of the results shown in Figure 4-1. At epoch 17:

- the gradient = 344.8687
- the validation checks reach 6
- the learning rate = 0.00039747

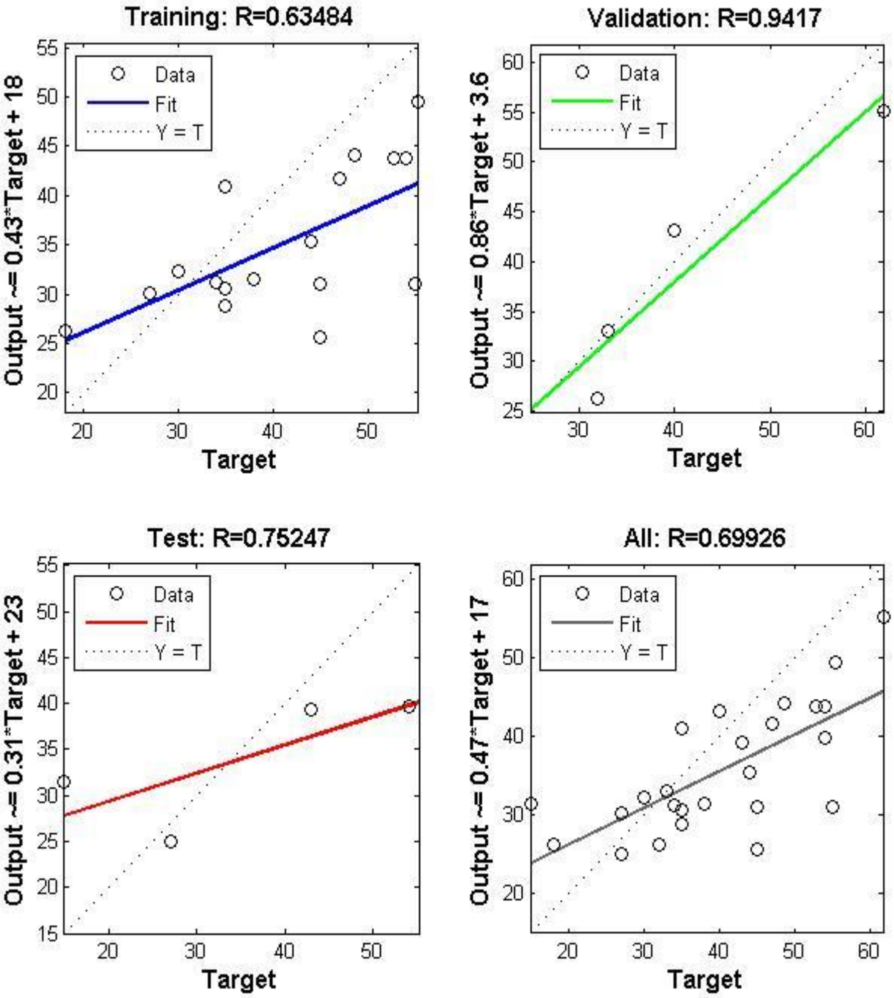


Figure 4-4- Class F Fly Ash and Ground-granulated Blast-furnace Slag Artificial Neural Network - Training Regression Plots

The regression plots shown in Figure 4-4 show the process in which the output data was computed. The first plot shows the outputs are calculated based on training, the second on validation and the third on test data. The final plot combines all three initial plots. The output data is then calculated from the formula:

$$Output \cong 0.47 \times Target + 17$$

The output data was then plotted along with the inputs to give input values of the materials required to create specific compressive strengths of GPC.

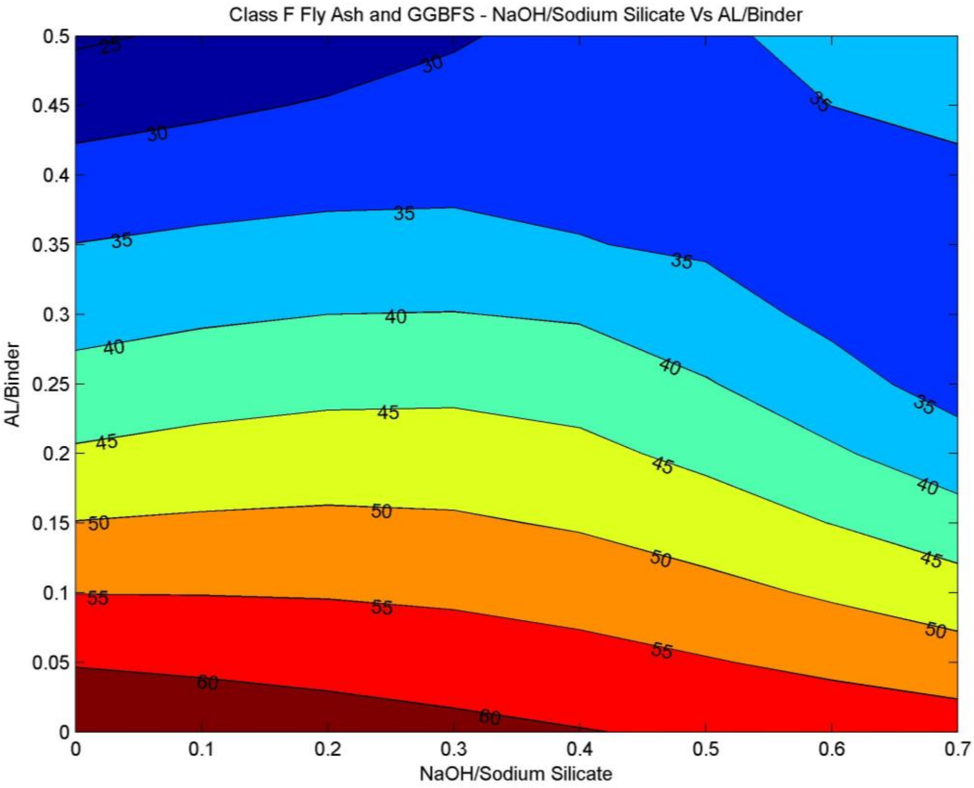


Figure 4-5 - Class F Fly Ash and Ground-granulated Blast-furnace Slag – Sodium Hydroxide/Sodium Silicate Vs Alkaline/Binder

An Alkaline/Binder ratio of 0.35 – 0.45 would be sufficient to create N32 GPC. With this range in mind, a NaOH/Sodium Silicate ratio of 0.4 would indicate an AL/Binder ratio of 0.4 would be ideal for N32 GPC.

The following table indicates material quantities for common concrete grades of GPC.

Table 4-2 Class F Fly Ash and Ground-granulated Blast-furnace Slag - Common Concrete Grade Quantities for Alkaline/Binder and Sodium Hydroxide/Sodium Silicate

Strength (MPa)	AL/Binder	NaOH/Sodium Silicate
32	0.35 – 0.45	0.3 – 0.5
40	0.25 – 0.3	0.28 – 0.55
50	0.12 – 0.16	0.2 – 0.6

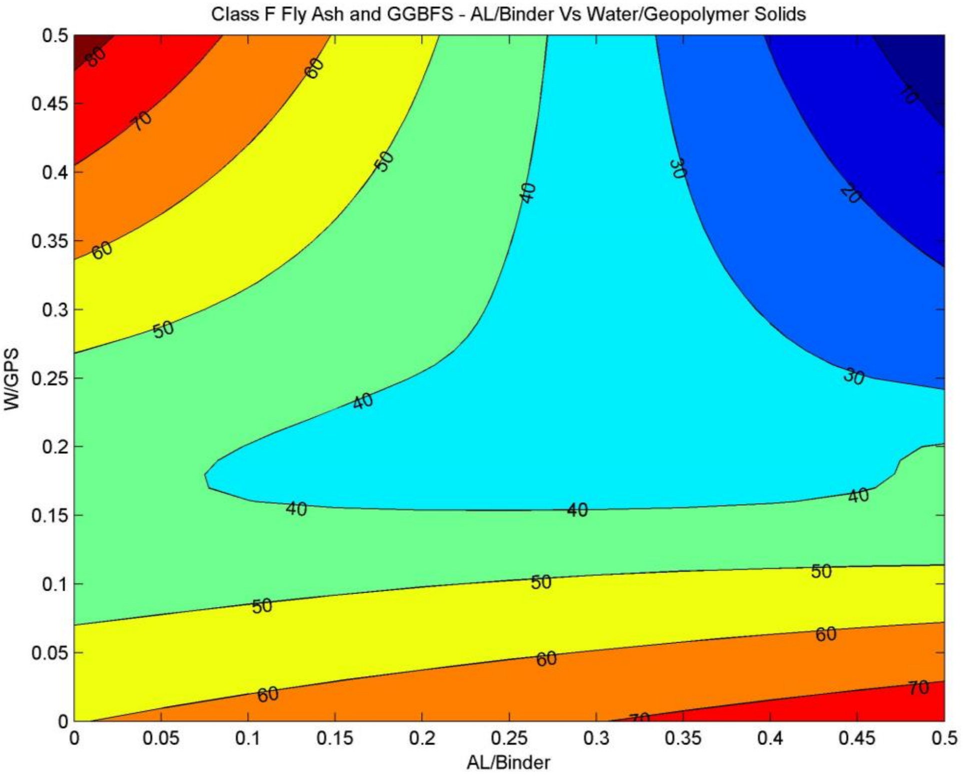


Figure 4-6 - Class F Fly Ash and Ground-granulated Blast-furnace Slag - Alkaline/Binder Vs Water/Geopolymer Solids

With an AL/Binder ratio of 0.4, Figure 4-6 indicates a range of W/GPS of 0.18 – 0.27. This range is similar to that shown in Table 3-2 and would indicate a W/GPS of 0.25 would be suitable for N32 GPC.

The following table indicates material quantities for common concrete grades of GPC.

Table 4-3 Class F Fly Ash and Ground-granulated Blast-furnace Slag - Common Concrete Grade Quantities for Alkaline/Binder and Water/Geopolymer Solids

Strength (MPa)	AL/Binder	W/GPS
32	0.35 – 0.45	0.18 – 0.27
40	0.25 – 0.3	0.17 – 0.18
50	0.12 – 0.16	0.07 – 0.09

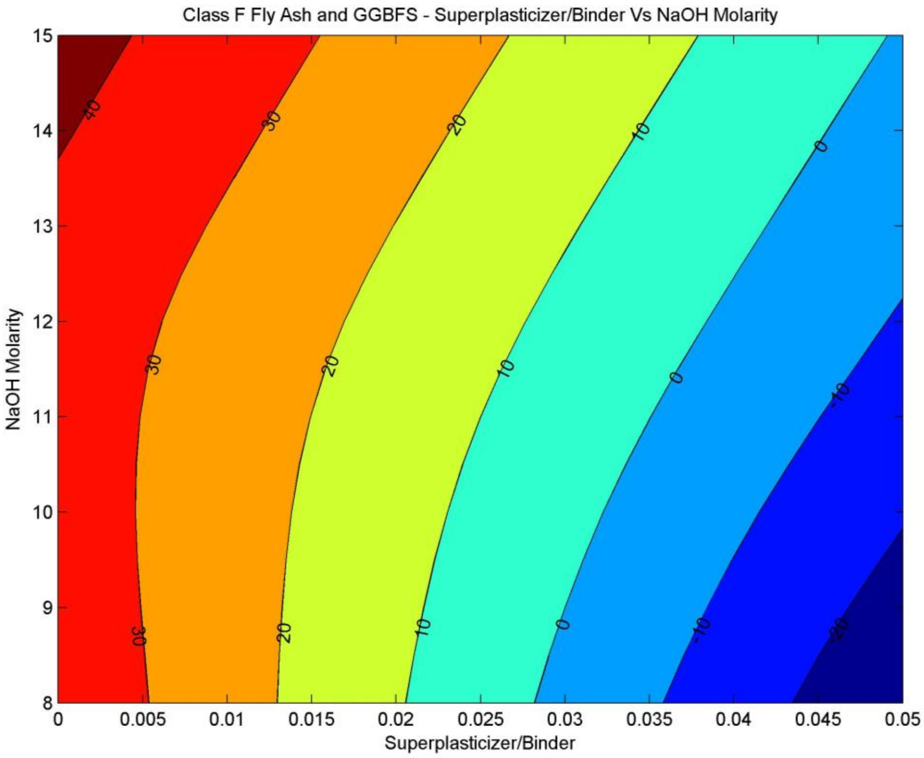


Figure 4-7 - Class F Fly Ash and Ground-granulated Blast-furnace Slag - Superplasticizer/Binder Vs Sodium Hydroxide Molarity

The results shown in Figure 4-7, the molarity of the NaOH solution can range from 8-12 for N32 GPC.

Choosing a NaOH molar weight of 8, the superplasticizer/binder ratio is from 0-0.005.

The following table indicates material quantities for common concrete grades of GPC.

Table 4-4 Class F Fly Ash and Ground-granulated Blast-furnace Slag - Common Concrete Grade Quantities for Superplasticizer/Binder and Sodium Hydroxide Molarity

Strength (MPa)	Superplasticizer/Binder	NaOH Molarity
32	0 – 0.005	8 – 12
40	0 – 0.005	≧14

Table 4-5 Class F Fly Ash and Ground-granulated Blast-furnace Slag – Artificial Neural Network Summary for N32 Geopolymer Concrete

AL/Binder	W/GPS	NaOH/Sodium Silicate	NaOH Molarity	Superplasticizer/Binder
0.3 - 0.45	0.18 – 0.27	0.3 – 0.5	8 - 12	0 - 0.05

This will be the only mixture tested for compressive strength due to time and material constraint. Six cylinders of 100mm diameter x 200mm high will be created to test for compressive strength of N32 GPC. This equates to approximately 0.0094m^3 of GPC, with some extra for spillage. Based on a concrete density of 2500kg/m^3, the weight of concrete required is approximately 35kg.

As the aggregates are based on OPC quantities, the percentages of course and fine aggregates will be the same as that for the Class F mix. Therefore, the total weight of aggregates is 28kg, with fine sands equalling 9.8kg of that.

From the database, the average fly ash/total weight ratio is 0.13, whilst the average slag/total weight ratio is 0.06. Therefore, 4.55kg of Class F FA and 2.1kg of GGBFS are required for this mix.

For the alkaline solution, the ratio of AL/Binder will be taken as 0.4. This would indicate a quantity of alkaline solution to be 2.66kg. Taking the NaOH/Sodium Silicate ratio as 0.4, this would indicate quantities:

- NaOH solution = 1.064kg
- Sodium Silicate solution = 1.596kg

Based on a W/GPS ratio of 0.25 and average percentages from the database:

- 55.9% water for hydroxide solution = 0.595L of water
- 57.9% water for silicate solution = 0.924L of water
- Extra Water = Approximately 0.43L
- Total water required = 1.95 litres

For the Superplasticizer, the super/binder ratio of 0.0025 will be used. Therefore, 0.02kg of Superplasticizer may be required.

Table 4-6 shows a summary of all materials required for the Class F FA and GGBFS test mix.

Table 4-6 Class F Fly Ash and Ground-granulated Blast-furnace Slag Mix Design Summary

Fly Ash (kg)	Slag (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticiser (kg)
4.55	2.1	18.2	9.8	1.06	8M	0.595	1.596	0.924	0.43	0.02

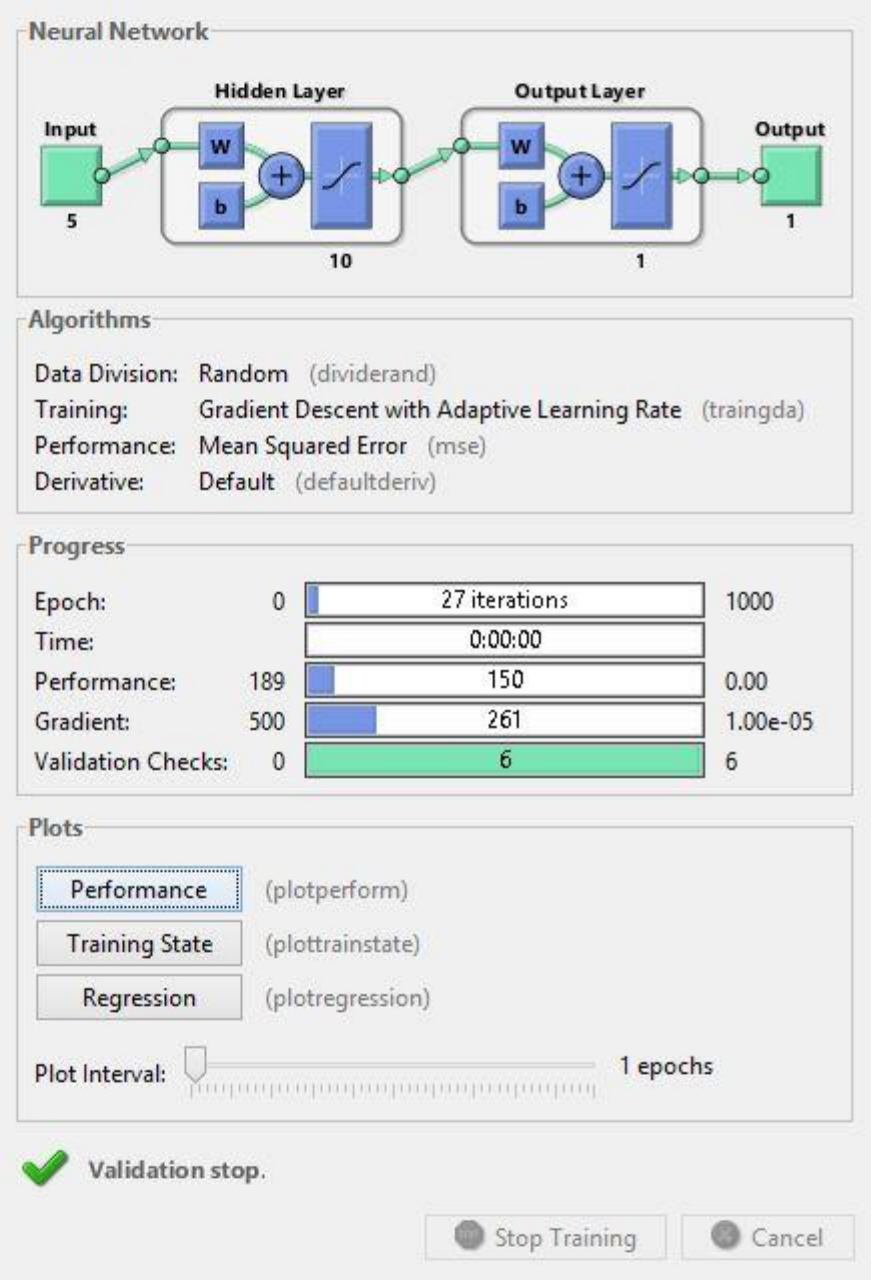
4.2 Class F Fly Ash Artificial Neural Network

The inputs were based on Class F Fly Ash (FA) being the binding material. The targets used for the neural network were the compressive strength of the mixes as found by others.

The inputs and outputs from the ANN for Class F FA are as shown in Table 4-7. For formatting reasons, only a sample of the complete table is shown here. For the complete table refer to Appendix C: Artificial Neural Network Data.

Table 4-7 Class F Fly Ash – Artificial Neural Network Inputs and Predicted Outputs

NaOh/Sodium Silicate	AL/FA	W/GPS	Super/Binder	NaOH Molarity	Actual Compressive Strength (Mpa)	Predicted Compressive Strength (MPa)
0.50	0.40	0.295	0.010	14	24	32.2044
0.40	0.40	0.251	0.020	14	30	35.3362
0.50	0.40	0.253	0.010	14	30	35.5241
0.40	0.35	0.220	0.020	14	32	40.7442
0.40	0.40	0.251	0.020	14	32	35.3362
0.50	0.40	0.253	0.010	8	32	34.5394
0.47	0.28	0.368	0.020	10	33.75	35.1475
0.40	0.46	0.209	0.021	12	34.59	41.8601
0.50	0.40	0.253	0.010	10	35	31.9175
0.47	0.29	0.384	0.020	10	35.25	33.5923
0.40	0.35	0.228	0.015	14	36	37.4533
0.50	0.35	0.217	0.013	14	37.09	38.8008
0.40	0.35	0.205	0.015	12	38	37.7634
0.50	0.40	0.253	0.010	14	38	35.5241
0.40	0.35	0.231	0.015	16	40	41.4564
0.40	0.35	0.210	0.015	14	40	39.9553
0.50	0.38	0.221	0.020	14	41	39.796
0.54	0.39	0.190	0.015	8	41.25	45.4373
0.40	0.35	0.230	0.015	16	42	41.6119
0.50	0.30	0.188	0.013	14	42.51	47.4435
0.40	0.50	0.328	0.070	12	44.81	45.3939
0.40	0.35	0.190	0.015	10	45	41.2809
0.40	0.35	0.219	0.015	14	45	38.6231
0.40	0.35	0.222	0.015	14	45	38.2155
0.50	0.40	0.253	0.010	14	46	35.5241
0.40	0.35	0.175	0.015	8	47	48.9683
0.40	0.50	0.328	0.070	12	47.99	45.3939



Algorithms

Data Division: Random (dividerand)
Training: Gradient Descent with Adaptive Learning Rate (traingda)
Performance: Mean Squared Error (mse)
Derivative: Default (defaultderiv)

Progress

Epoch: 0 | 27 iterations | 1000
Time: | 0:00:00 |
Performance: 189 | 150 | 0.00
Gradient: 500 | 261 | 1.00e-05
Validation Checks: 0 | 6 | 6

✓ Validation stop.

Figure 4-8 - Class F Fly Ash Artificial Neural Network - Training Results

The selected algorithms used for the Class F Fly Ash ANN are shown at the top of Figure 4-8. This reflects that previously mentioned, with the traingda and mean square error algorithms used. At the end of the training:

- 27 epochs out of a maximum 1000 were used
- The time taken was instantanous
- Performance was 150 out of 189
- The gradient was 261
- And 6 validation checks were performed

Figure 4-8 indicates that the validation checks were the reason why the training was stopped.

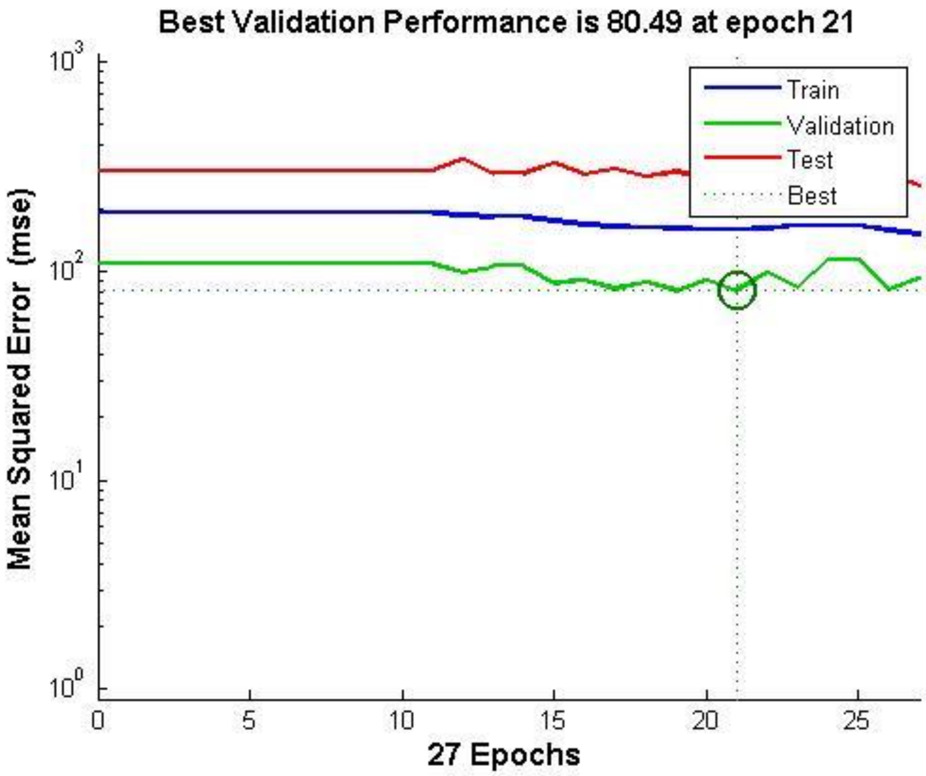


Figure 4-9 - Class F Fly Ash Artificial Neural Network - Training Performance Plot

As shown in Figure 4-9, the performance of the training was best at epoch 21 with the best validation being 80.49.

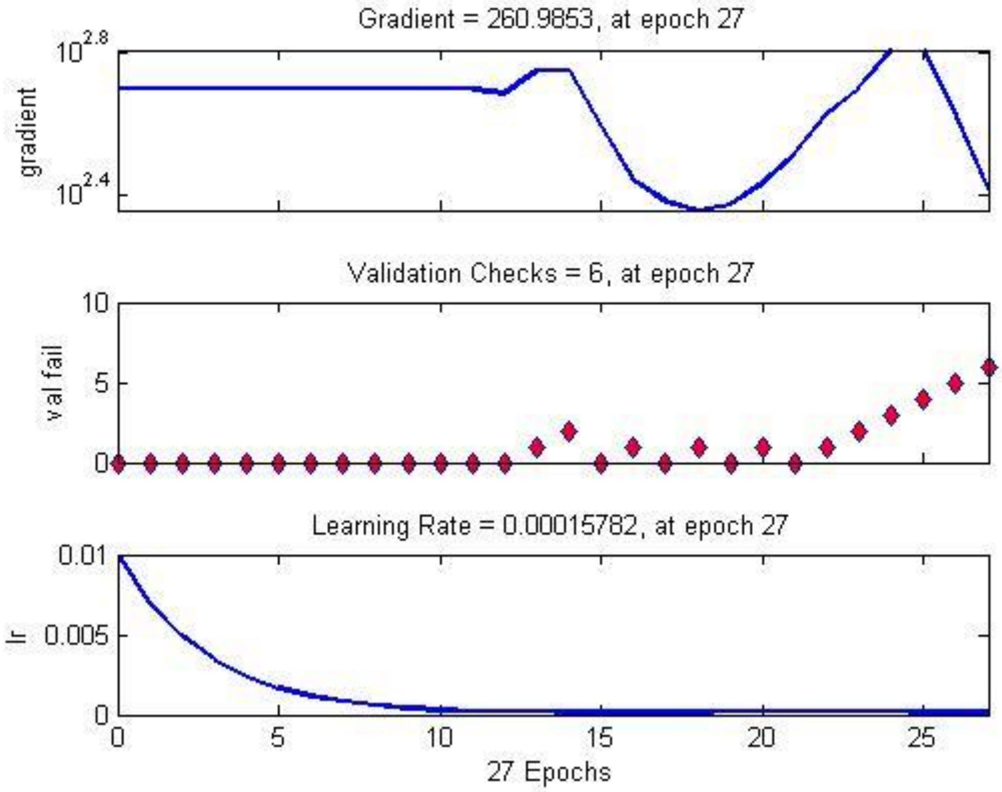


Figure 4-10 - Class F Fly Ash Artificial Neural Network - Training State Plot

The plots shown in Figure 4-10 from the training state plot. It shows the pattern of the results shown in Figure 4-8. At epoch 27:

- the gradient = 260.9853
- the validation checks reach 6
- the learning rate = 0.00015782

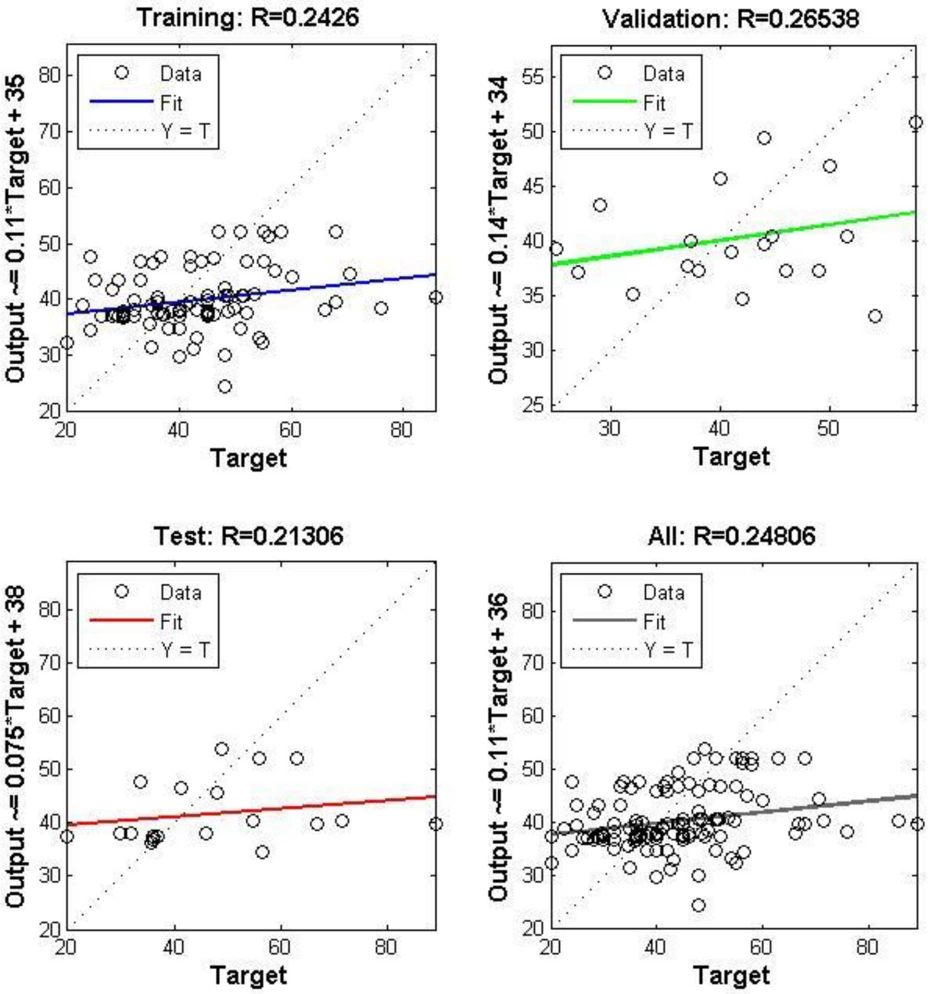


Figure 4-11 - Class F Fly Ash Artificial Neural Network Regression Plots

The regression plots shown in Figure 4-11 show the process in which the output data was computed. The first plot shows the outputs are calculated based on training, the second on validation and the third on test data. The final plot combines all three initial plots. The output data is then calculated from the formula:

$$Output \cong 0.11 \times Target + 36$$

The output data was then plotted along with the inputs to give input values of the materials required to create specific compressive strengths of GPC.

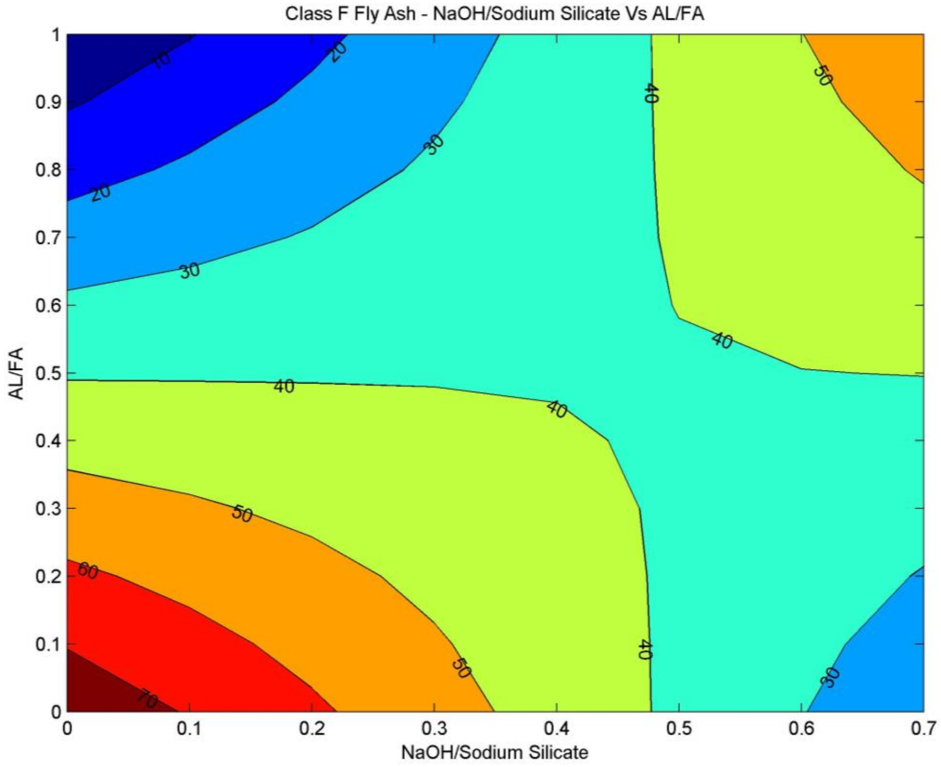


Figure 4-12 - Class F Fly Ash – Sodium Hydroxide/Sodium Silicate Vs Alkaline/Fly Ash

As shown in Chapter 3.1.2, an AL/FA ratio of 0.4 - 0.6 is what is required to create a mix design for N32 GPC. Using this value in Figure 4-12 to align with the contours, which represent compressive strength, would indicate a range for sodium hydroxide/sodium silicate ratio of 0.4 - 0.6.

Other common grades of concrete are as follows:

Table 4-8 Class F Fly Ash - Common Concrete Grade Quantities for Alkaline/Fly Ash and Sodium Hydroxide/Sodium Silicate

Strength (MPa)	AL/FA	NaOH/Sodium Silicate
25	0.7 – 0.9	0.1 – 0.25
32	0.4 – 0.6	0.4 – 0.6
40	0.5– 0.8	0.4 – 0.6
50	0.1 – 0.25	0.27 – 0.38

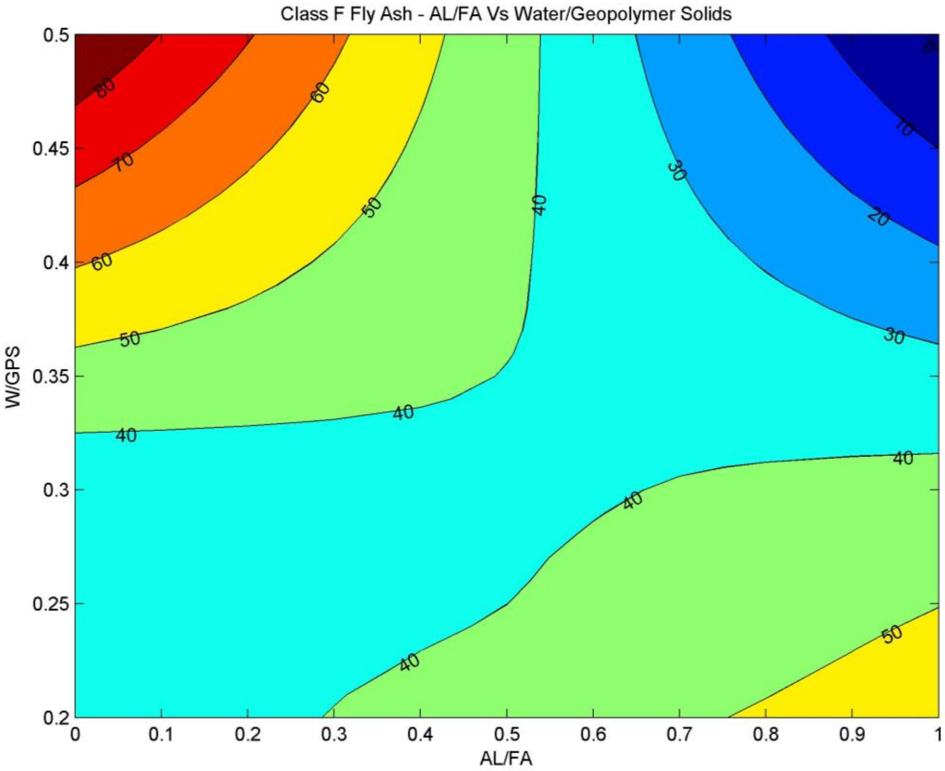


Figure 4-13 - Class F Fly Ash - Alkaline/Fly Ash Vs Water/Geopolymer Solids

The results shown in Figure 4-13, along with that from Figure 4-12, indicate that the ratio of water to geopolymer solids would need to be approximately 0.45 to create N32 GPC. This result concurs that shown by Ferdous, Manalo et al. (2015), in that the lower W/GPS ratio results in higher strength concrete. This however, is very high in comparison to that shown by Lloyd, N. A. and B. V. Rangan (2010). If a AL/FA ratio of 0.4 – 0.6 is used then the W/GPS ratio would be 0.4. For the purpose of this report a W/GPS ratio of 0.4 will be used. The values shown in Table 4-9 are similar to that by previous research except for 50MPa concrete. This value seems a little high and as such would require testing to check.

Table 4-9 Class F Fly Ash - Common Concrete Grade Quantities for Alkaline/Fly Ash Vs Water/Geopolymer Solids

Strength (MPa)	AL/FA	W/GPS
25	0.7 – 0.9	0.4 – 0.45
32	0.4 – 0.6	0.27 – 0.35
40	0.5 – 0.8	0.25 – 0.3
50	0.1 – 0.25	0.35 – 0.38

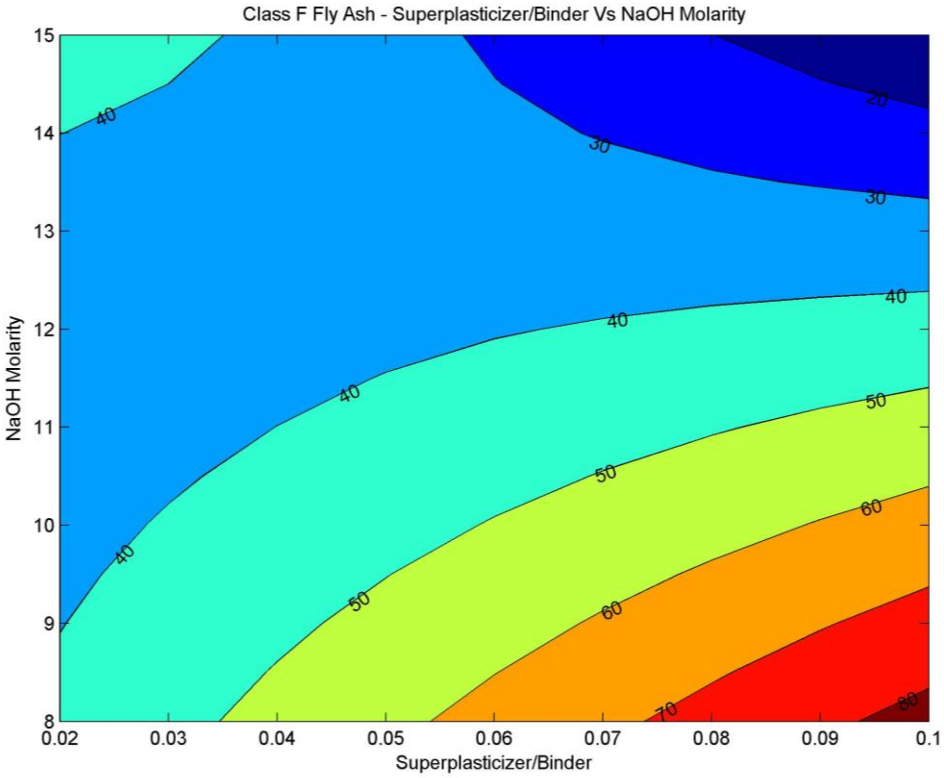


Figure 4-14 - Class F Fly Ash - Superplasticizer/Binder Ratio Vs Sodium Hydroxide Molarity

Figure 4-14 shows the relationship between superplasticizer/binder ratio and the molarity of the NaOH solution. It is evident that as the molarity of the NaOH solution increases, so too does the ratio of the superplasticizer to binder. For N32 concrete, NaOH molarity range of 12–14 with superplasticizer/binder ratio range of 0.04 – 0.1.

Table 4-10 Class F Fly Ash - Common Concrete Grade Quantities for Superplasticizer/Binder and Sodium Hydroxide Molarity

Strength (MPa)	Superplasticizer/Binder	NaOH Molarity
32	0.04 – 0.1	12 - 14
40	0.02 – 0.1	9 - 12
50	0.035 – 0.06	8 - 10

Table 4-11 Class F Fly Ash Artificial Neural Network Summary for N32 Geopolymer Concrete

AL/FA	W/GPS	NaOH/Sodium Silicate	NaOH Molarity	Superplasticizer/Binder
0.4 - 0.6	0.27 – 0.35	0.4 – 0.6	12 – 14	0.04 – 0.1

4.3 Class C Fly Ash Artificial Neural Network

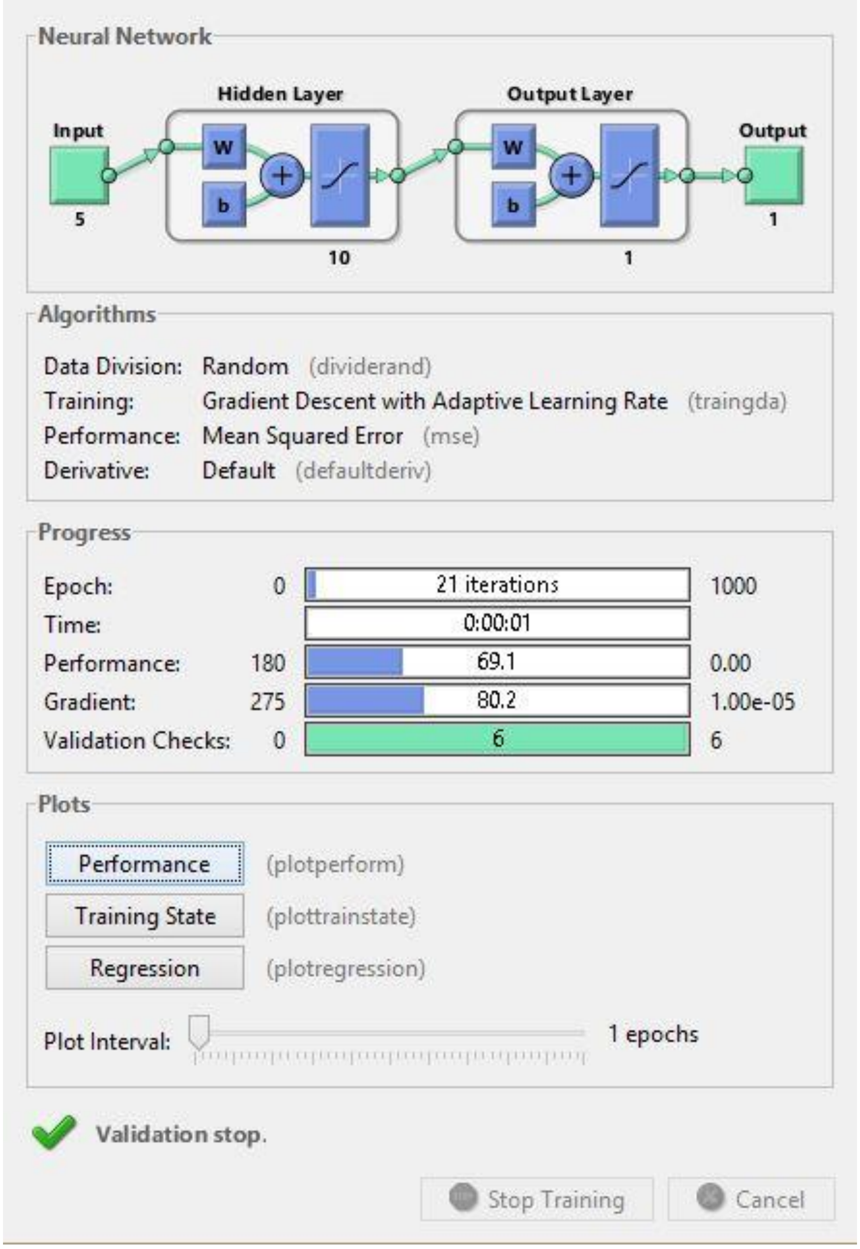
Similarly to the Class F Fly Ash ANN, the inputs were based on Class C Fly Ash (FA) being the binding material. The targets used for the neural network were the compressive strength of the mixes as found by others.

The inputs and outputs from the ANN for Class C Fly Ash are as shown in Table 4-12.

Table 4-12 Class C Fly Ash - Artificial Neural Network Inputs and Predicted Outputs

NaOH/Sodium Silicate	AL/FA	W/GPS	Super/Binder	NaOH Molarity	Compressive Strength (MPa)	Predicted
0.49	0.51	0.295	0.12	20	26	26.00858
1.00	0.51	0.293	0.08	20	30	26.01635
0.50	0.51	0.295	0.1	20	32	26.00763
0.50	0.50	0.222	0	10	33.8	51.97201
0.49	0.51	0.239	0	10	36	51.99943
1.00	0.50	0.229	0	20	37.64	50.51782
0.49	0.51	0.267	0.03	15	38	40.01598
0.50	0.50	0.222	0	15	39.02	51.9274
1.00	0.50	0.229	0	10	39.67	51.99362
2.00	0.51	0.272	0.06	15	40	38.03645
2.00	0.51	0.300	0.1	20	42	26.25172
0.50	0.51	0.267	0.05	15	43	36.20412
1.00	0.51	0.265	0.04	15	45	44.38765
1.00	0.50	0.229	0	15	45.34	51.9729
0.50	0.50	0.222	0	20	46.69	51.66551
1.00	0.51	0.237	0	10	48	51.99888
2.00	0.51	0.254	0.03	10	48	51.98213
0.50	0.51	0.239	0	10	52	51.99943

The data range available for Class C FA was relatively miniscule in comparison to that shown from the Class F FA database. As such, the results from the ANN were not as accurate as that shown in the Class F ANN.



Data Division: Random (dividerand)
Training: Gradient Descent with Adaptive Learning Rate (traingda)
Performance: Mean Squared Error (mse)
Derivative: Default (defaultderiv)

Epoch:	0	21 iterations	1000
Time:		0:00:01	
Performance:	180	69.1	0.00
Gradient:	275	80.2	1.00e-05
Validation Checks:	0	6	6

(plotperform)
(plottrainstate)
(plotregression)
Plot Interval: 1 epochs

✓ Validation stop.

Figure 4-15 Class C Fly Ash Artificial Neural Network - Training Results

The training results shown above indicate an adequate level of data training was performed. The selected algorithms used for the Class C FA ANN are shown at the top of Figure 4-15. This is the same process performed for Class F FA ANN. At the end of the training:

- 21 epochs out of a maximum 1000 were used
- The time taken was 0:00:01.
- Performance was 69.1 out of 180
- The gradient was 80.2
- And 6 validation checks were performed

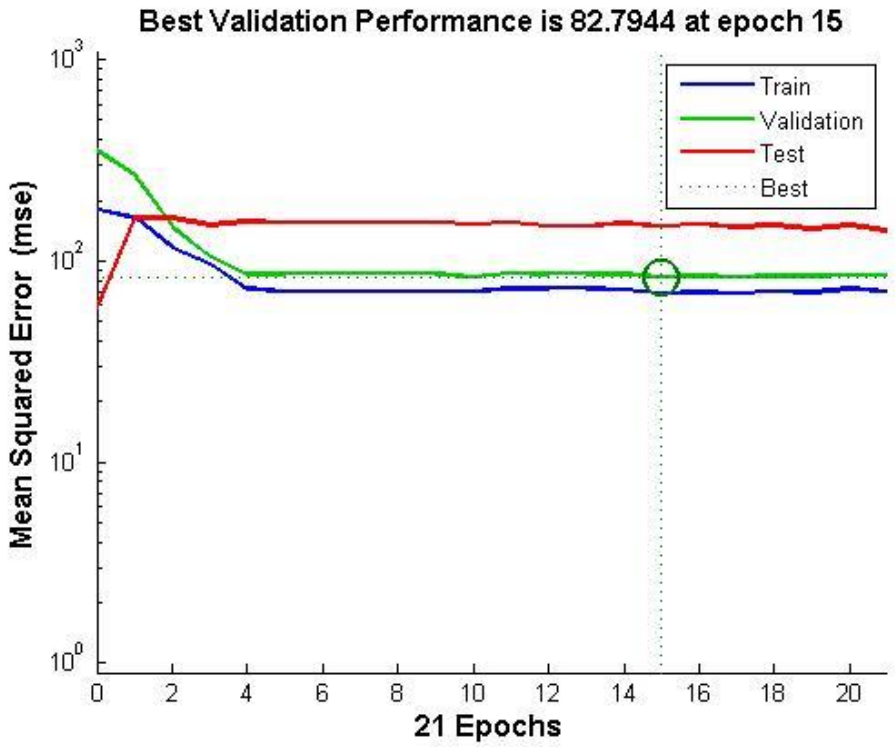


Figure 4-16 Class C Fly Ash Artificial Neural Network - Training Performance Plot

As shown in Figure 4-16, the performance of the training was best at epoch 15 with the best validation being 82.7944.

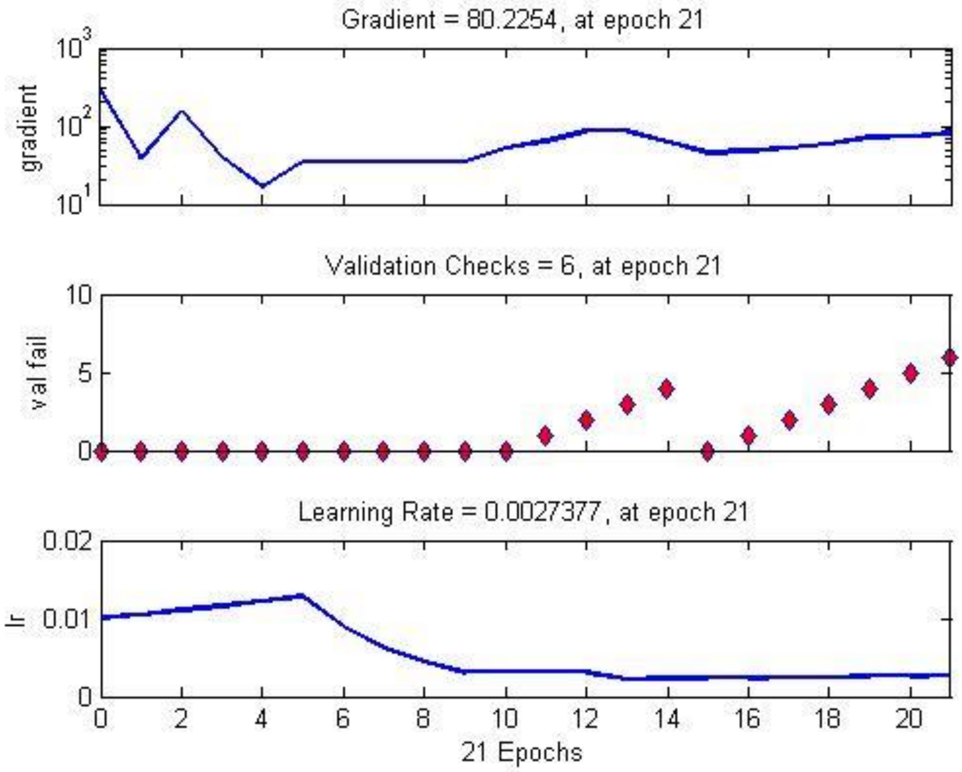


Figure 4-17 Class C Fly Ash Artificial Neural Network - Training State Plot

The plots shown in Figure 4-17 from the training state plot. It shows the pattern of the results shown in Figure 4-15. At epoch 21:

- the gradient = 80.2254
- the validation checks reach 6
- the learning rate = 0.0027377

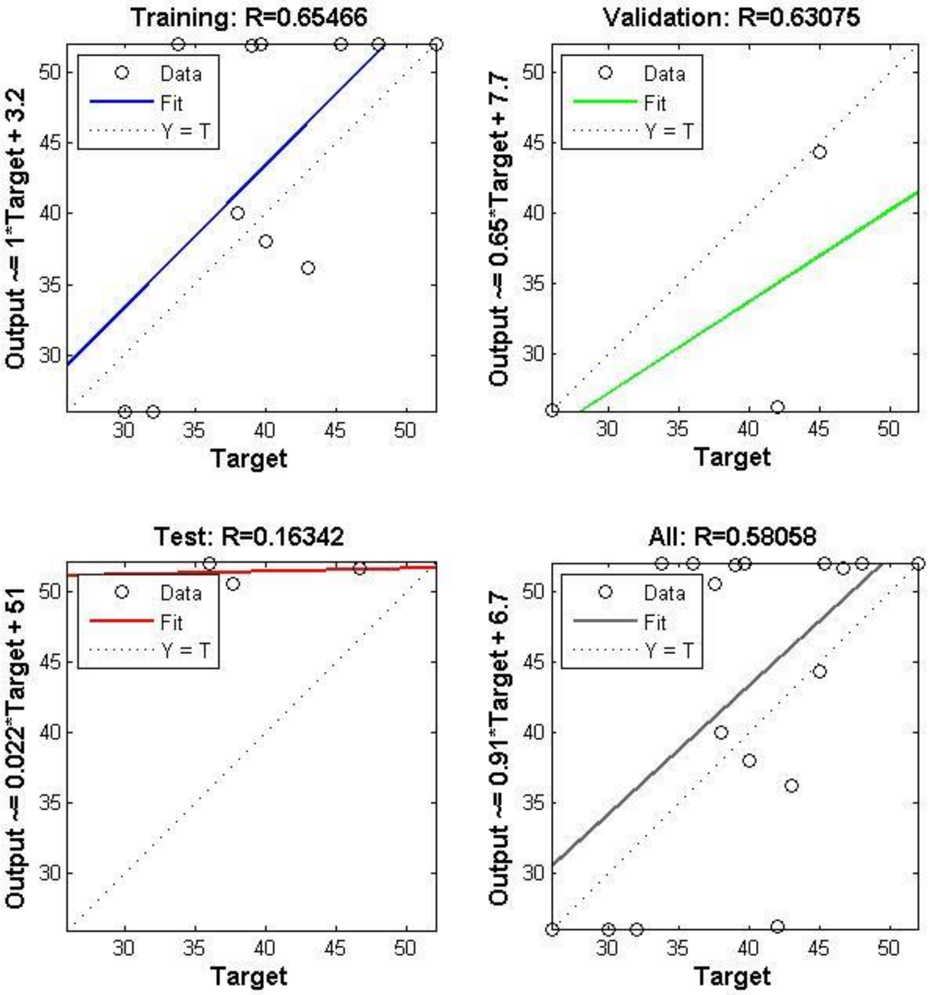


Figure 4-18 Class C Fly Ash Artificial Neural Network Regression Plots

The regression plots shown in Figure 4-18 show the process in which the output data was computed. The first plot shows the outputs are calculated based on training, the second on validation and the third on test data. The final plot combines all three initial plots. As shown in all plots, the line of best-fit is not very accurate to most of the data points, this is because the input data was very limited and not many consistencies could be noted in the material quantities used. The equation for the line of best-fit is as shown below:

$$Output \ \cong 0.91 \times Target + 6.7$$

The output data was then plotted along with the inputs to give input values of the materials required to create specific compressive strengths of GPC.

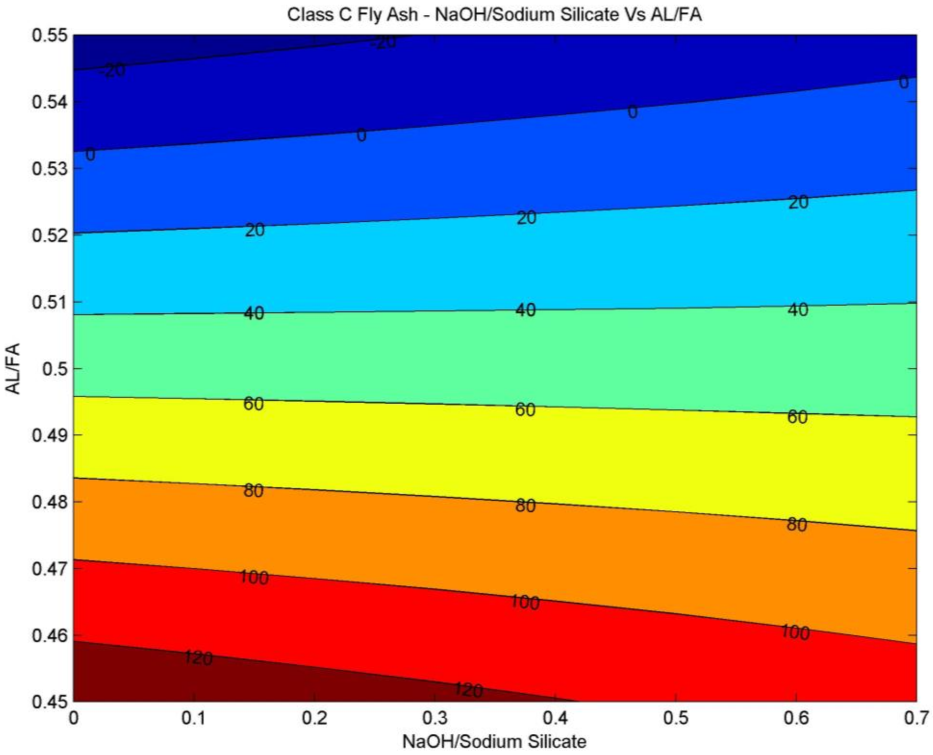


Figure 4-19 Class C Fly Ash – Sodium Hydroxide/Sodium Silicate Vs Alkaline/Fly Ash

As the data was fairly limited, the contour plot as shown in Figure 4-19, is not very limiting in the range of materials that could be chosen. It does however, indicate that a minimum AL/FA ratio of 0.51 shall be required to create a mix design for N32 concrete. The selection of an appropriate amount of hydroxide/silicate is not as simple. As such, a review of Table 4-12, and comparing the predicted compressive strengths and that of previous research, would be required to obtain the ultimate mix. The quantities of NaOH/Sodium Silicate in Table 4-12 vary quite a lot. Taking the ratios of the closest predicted strengths, indicates that a range of 0.4-0.51 is required for all grades of concrete. This, combined with Figure 4-19, shows that as the grade of concrete increases so too does the quantity of FA. This would be similar to that of OPC, where the cement content would increase with the strength.

The quantities for common grades of concrete are as follows:

Table 4-13 Class C Fly Ash - Common Concrete Grade Quantities for Alkaline/Fly Ash and Sodium Hydroxide/Sodium Silicate

Strength (MPa)	AL/FA	NaOH/Sodium Silicate
25	0.515	0.4 – 0.51
32	0.51	0.4 – 0.51
40	0.505	0.4 – 0.51
50	0.5	0.4 – 0.51

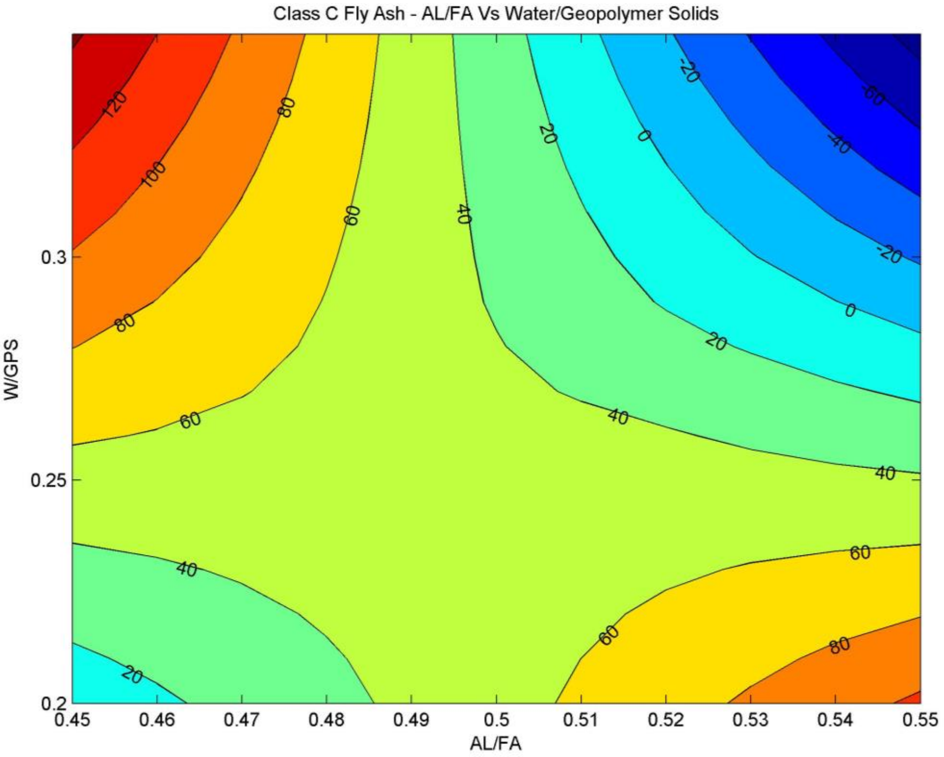


Figure 4-20 Class C Fly Ash - Alkaline/Fly Ash Vs Water/Geopolymer Solids

The results shown in Figure 4-20, along with that from Figure 4-19, indicate that the ratio of water to geopolymer solids would need to be approximately 0.29 to create N32 GPC. This result concurs that shown by Chindaprasirt, et al (2007).

Table 4-14 Class C Fly Ash - Common Concrete Grade Quantities for Alkaline/Fly Ash Vs Water/Geopolymer Solids

Strength (MPa)	AL/FA	W/GPS
25	0.515	0.3
32	0.51	0.29
40	0.505	0.275
50	0.5	0.25

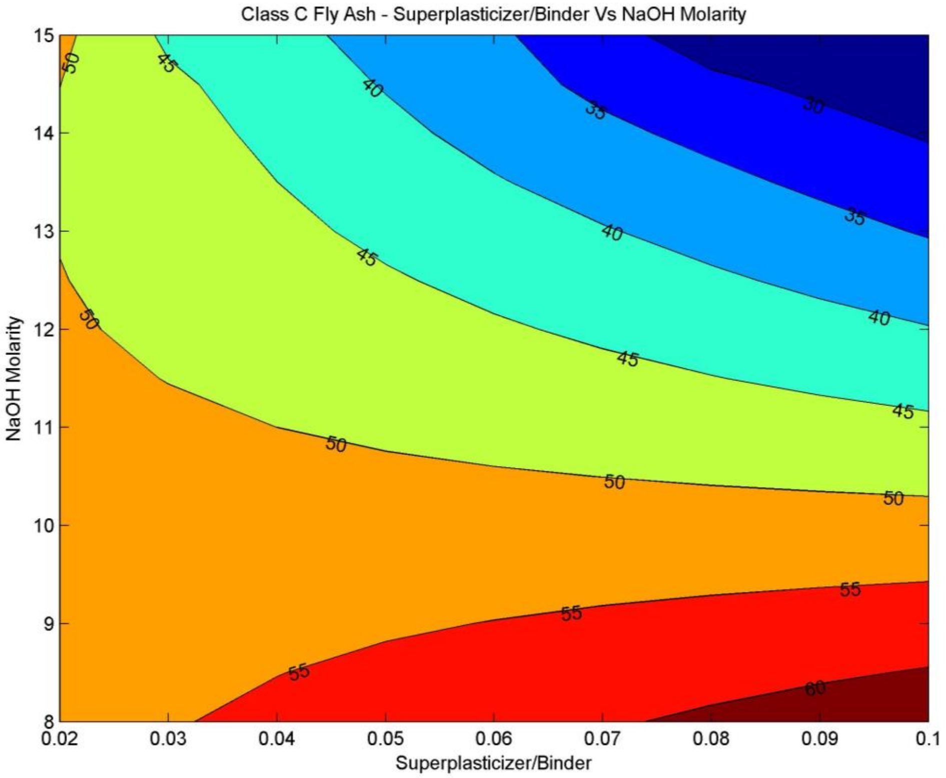


Figure 4-21 Class C Fly Ash - Superplasticizer/Binder Ratio Vs Sodium Hydroxide Molarity

Figure 4-21 shows the relationship between superplasticizer/binder ratio and the molarity of the NaOH solution. It indicates that as the molarity of the NaOH solution decreases, the compressive strength increases. It also shows that superplasticizer is required for all mixes. This would indicate that the workability of the mix is low, which concurs with that shown by Chindaprasirt, et al (2007). For N32 GPC, NaOH molarity range of 13–15 with superplasticizer/binder ratio range of 0.065 – 0.1.

Table 4-15 Class C Fly Ash - Common Concrete Grade Quantities for Superplasticizer/Binder and Sodium Hydroxide Molarity

Strength (MPa)	Superplasticizer/Binder	NaOH Molarity
32	0.065 – 0.1	13 - 15
40	0.05 – 0.1	12 - 14
50	0.025 – 0.045	11 - 12

Table 4-16 Class C Fly Ash Artificial Neural Network Summary for N32 Geopolymer Concrete

AL/FA	W/GPS	NaOH/Sodium Silicate	NaOH Molarity	Superplasticizer/Binder
0.51	0.29	0.4 – 0.51	13 – 15	0.065 – 0.1

4.4 Ground-granulated Blast-furnace Slag Artificial Neural Network

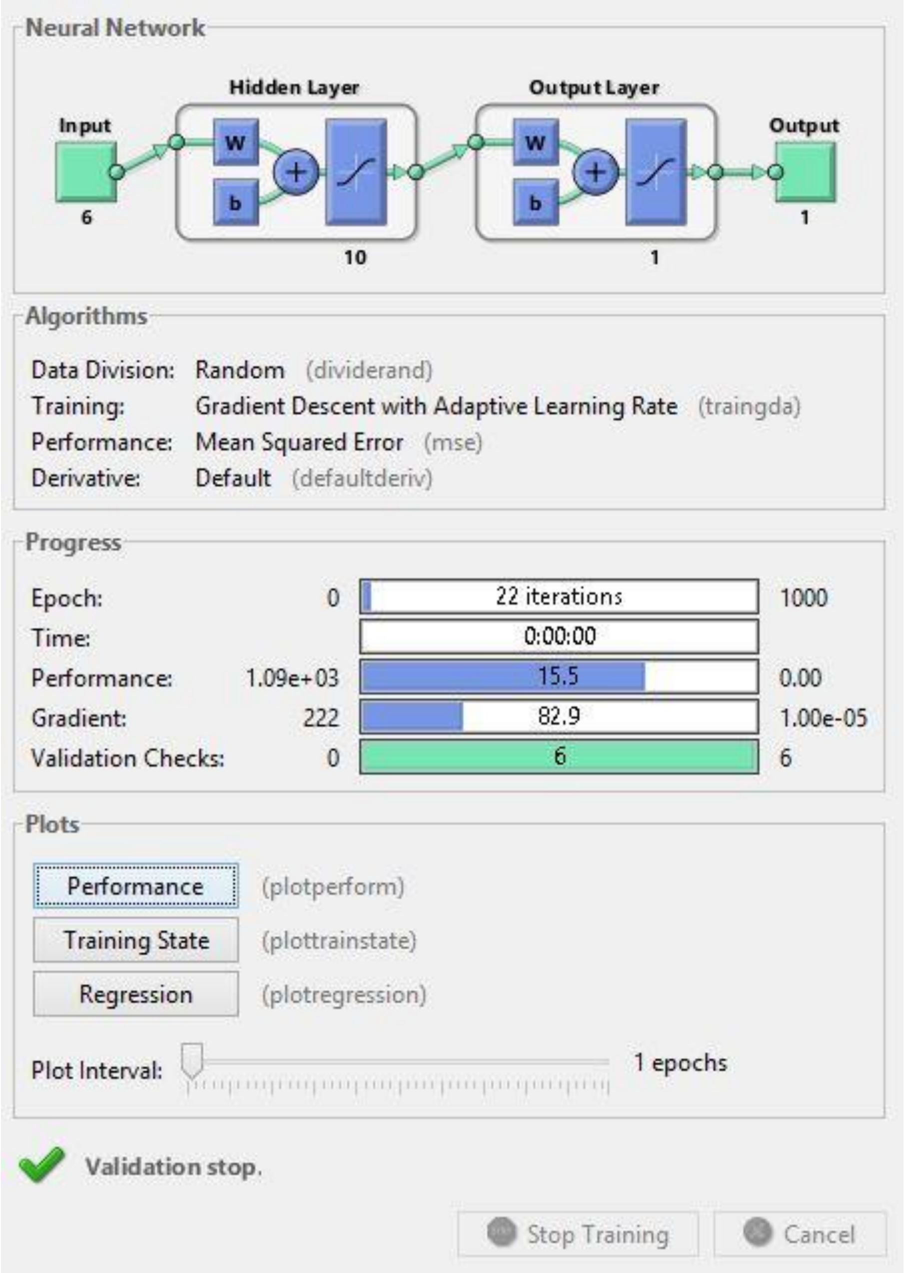
Similarly to the Class F fly ash ANN, the inputs were based on GGBFS being the binding material. The targets used for the neural network were the compressive strength of the mixes as found by others.

The inputs and outputs from the ANN for GGBFS are as shown in Table 4-17.

Table 4-17 Ground-granulated Blast-furnace Slag – Artificial Neural Network Inputs and Predicted Outputs

Slag/Total Weight	Coarse Agg/Total Weight	Sand/total weight	NaOH /Sodium Silicate	AL/Slag	W/GPS	Actual Compressive Strength (MPa)	Predicted Compressive Strength (MPa)
0.16	0.35	0.35	3.00	0.28	0.49	22	24.4
0.16	0.34	0.34	1.00	0.38	0.49	35	24.1
0.16	0.50	0.25	5.00	0.40	0.33	38.1	49.6
0.16	0.50	0.25	3.00	0.45	0.29	50.26	55.5
0.15	0.52	0.26	3.00	0.40	0.32	53.8	59.0
0.14	0.52	0.26	5.00	0.50	0.26	56.67	56.4
0.15	0.50	0.25	1.00	0.50	0.33	57.18	60.0
0.17	0.49	0.24	1.00	0.40	0.33	57.4	54.6
0.17	0.49	0.24	5.01	0.45	0.30	58.11	46.5
0.16	0.49	0.24	3.00	0.50	0.32	60.8	52.5
0.14	0.52	0.26	1.00	0.45	0.35	65.02	62.9

Due to the limited amount of available research data, it was decided to increase the amount of inputs for the ANN by including the ratios of slag, coarse aggregate and sand to the total weight respectively. It was also noted that no superplasticizer was used in any of the mixes and as such it was left out of the inputs for the ANN. The molarity of the NaOH solution was not mentioned in most research papers either so it was left out for all inputs.



Algorithms

Data Division: Random (dividerand)
Training: Gradient Descent with Adaptive Learning Rate (traingda)
Performance: Mean Squared Error (mse)
Derivative: Default (defaultderiv)

Progress

Epoch:	0	22 iterations	1000
Time:		0:00:00	
Performance:	1.09e+03	15.5	0.00
Gradient:	222	82.9	1.00e-05
Validation Checks:	0	6	6

Validation stop.

Figure 4-22 Ground-granulated Blast-furnace Slag Artificial Neural Network - Training Results

The training results shown above indicate an adequate level of data training was performed. The selected algorithms used for the GGBFS ANN are shown at the top of Figure 4-22. At the end of the training:

- 22 epochs out of a maximum 1000 were used
- The time taken was 0:00:00.
- Performance was 15.5 out of 1090
- The gradient was 82.9
- And 6 validation checks were performed

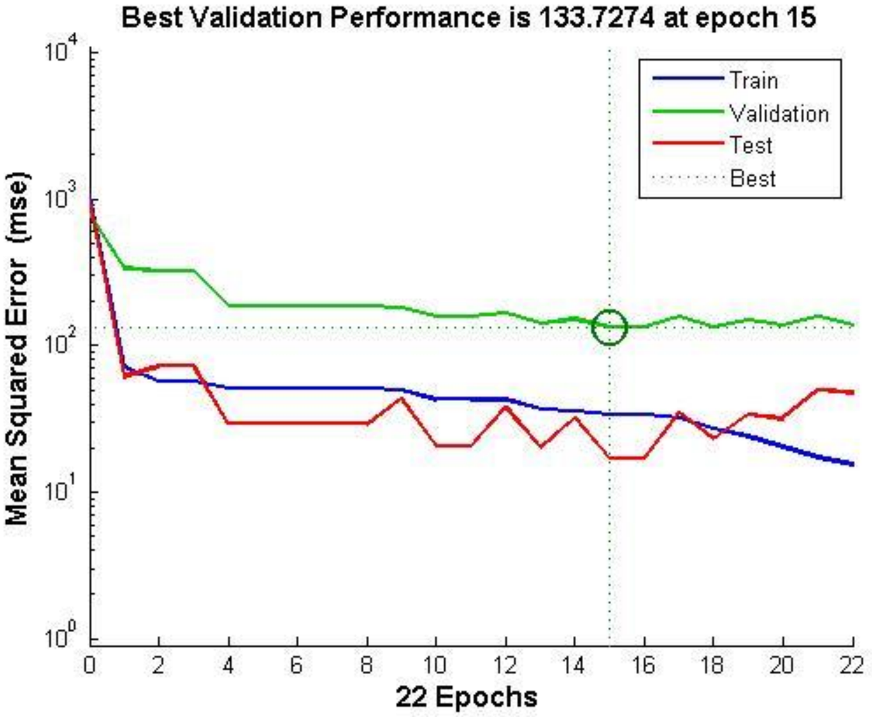


Figure 4-23 Ground-granulated Blast-furnace Slag Artificial Neural Network - Training Performance Plot

As shown above, the performance of the training was best at epoch 15 with the best validation being 133.7274.

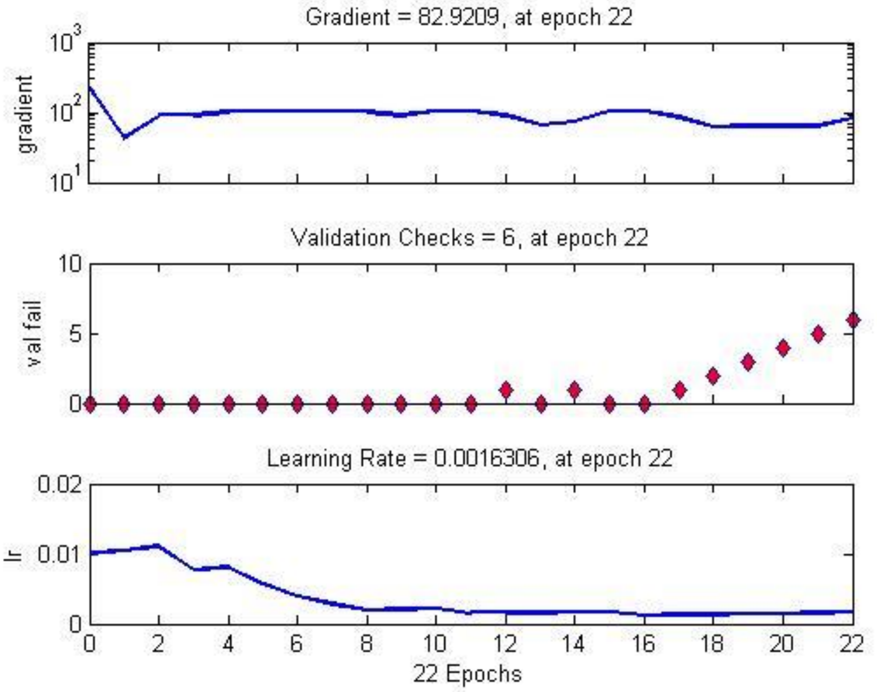


Figure 4-24 Ground-granulated Blast-furnace Slag Artificial Neural Network - Training State Plot

The plots shown in Figure 4-24 are from the training state plot. It shows the pattern of the results shown in Figure 4-22. At epoch 22:

- the gradient = 82.9209
- the validation checks reach 6
- the learning rate = 0.0016306

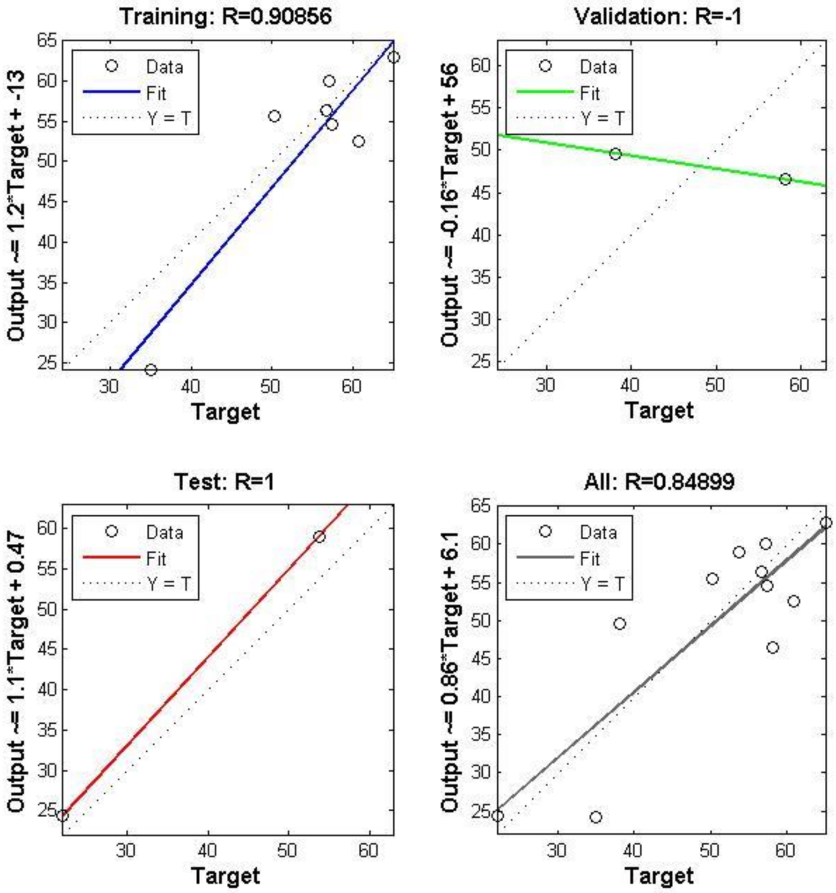


Figure 4-25 Ground-granulated Blast-furnace Slag Artificial Neural Network Regression Plots

The regression plots shown in Figure 4-25 show the process in which the output data was computed. Similar to the Class C FA ANN results, the line of best-fit is not very accurate to most of the data points, this is because the input data was very limited and not many consistencies could be noted in the material quantities used. The equation for the line of best-fit is as shown below:

$$Output \cong 0.86 \times Target + 6.1$$

The output data was then plotted along with the inputs to give input values of the materials required to create specific compressive strengths of GPC.

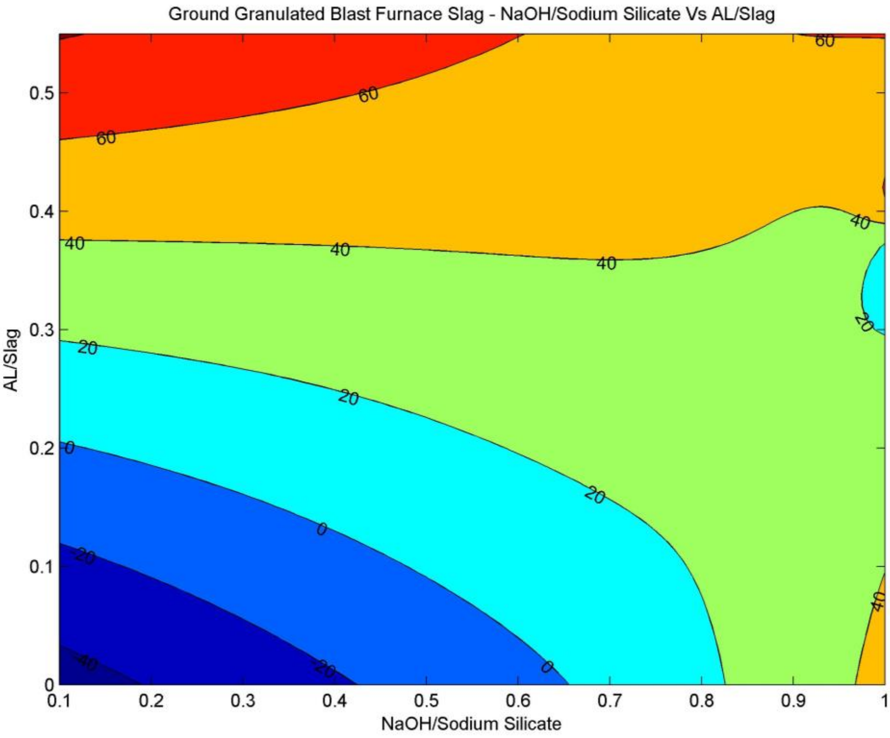


Figure 4-26 Ground-granulated Blast-furnace Slag – Sodium Hydroxide/Sodium Silicate Vs Alkaline/Slag

From Figure 4-26, the ratios of AL/slag and NaOH/Sodium silicate can be determined for standard concrete grades.

The quantities for common grades of concrete are as follows:

Table 4-18 Ground-granulated Blast-furnace Slag - Common Concrete Grade Quantities for Alkaline/Slag and Sodium Hydroxide/Sodium Silicate

Strength (MPa)	AL/Slag	NaOH/Sodium Silicate
32	0.32	0.4-0.7
40	0.38	0.4-0.7
50	0.42	0.4-0.7

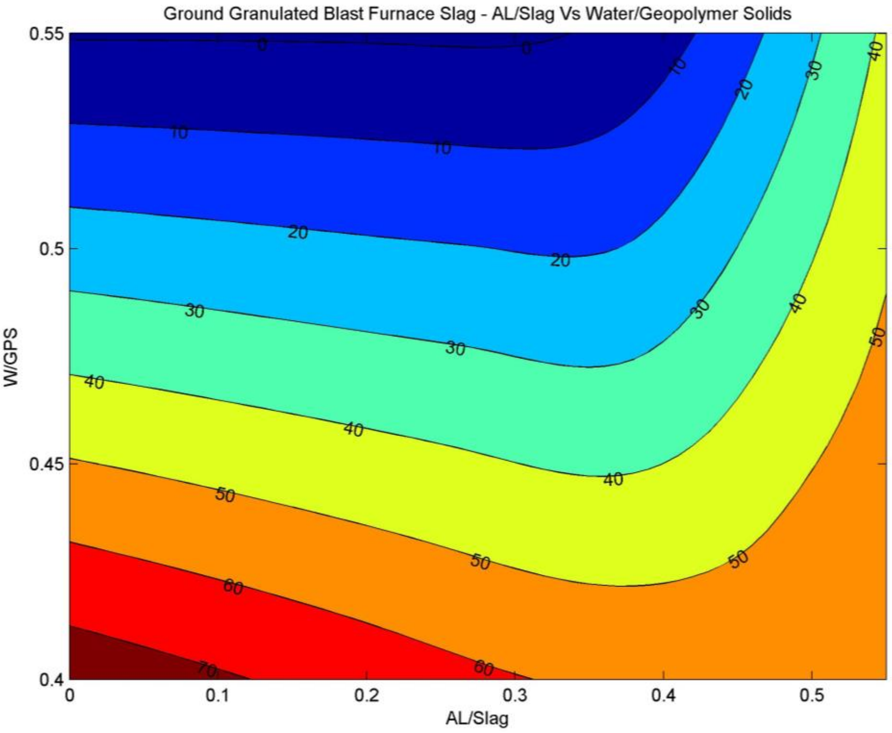


Figure 4-27 Ground-granulated Blast-furnace Slag - Alkaline/Slag Vs Water/Geopolymer Solids

The results shown in Figure 4-27, along with that from Figure 4-26, indicate that the ratio of water to geopolymer solids would need to be approximately 0.47 to create N32 concrete. This result concurs that shown by Bernal et al (2012).

Table 4-19 Ground-granulated Blast-furnace Slag - Common Concrete Grade Quantities for Alkaline/Slag and Water/Geopolymer Solids

Strength (MPa)	AL/Slag	W/GPS
32	0.32	0.47
40	0.38	0.45
50	0.42	0.42

Table 4-20 Ground-granulated Blast-furnace Slag Artificial Neural Network Summary for N32 Geopolymer Concrete

AL/Slag	W/GPS	NaOH/Sodium Silicate
0.32	0.47	0.4-0.7

CHAPTER 5 TESTING

5.1 Mixing of Materials

With the use of the material quantities established from the Artificial Neural Networks (ANNs) in Chapter 4, the mix could then be created and set into moulds for later testing. The materials were gathered and mixed in lab Z1 at University of Southern Queensland's (USQ) Toowoomba Campus on 25 August 2015. The materials that were used are as per that shown in Table 4-6 except for the one item, the superplasticizer. The university did not hold any superplasticizer during the mixing period and as such it was left out of the mix. The remaining material quantities were as per Table 4-6.

The first step was to mix the alkaline solution. The sodium hydroxide pellets from Chem Supply were added to water. As the pellets dissolved, the solution generated heat. As such it was left to cool down whilst the other materials were mixed.

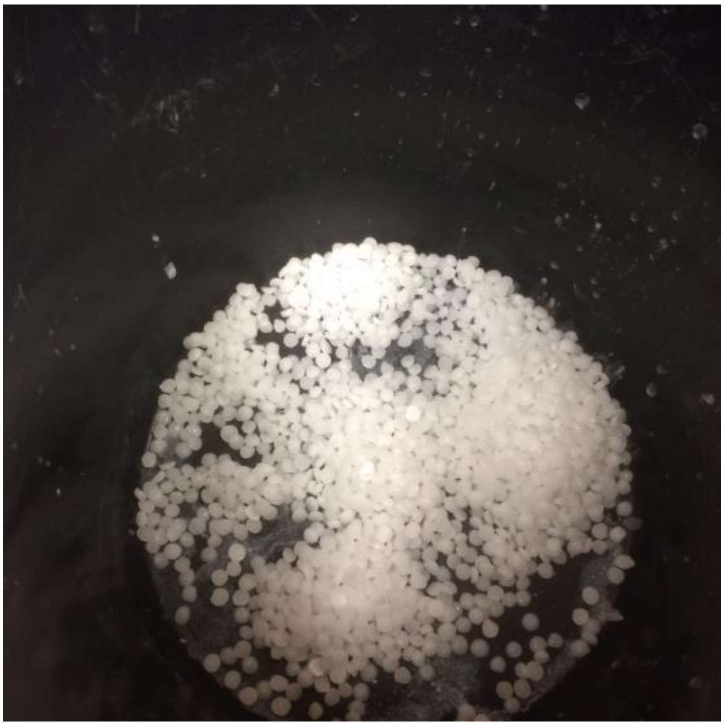


Figure 5-1 Sodium Hydroxide Pellets

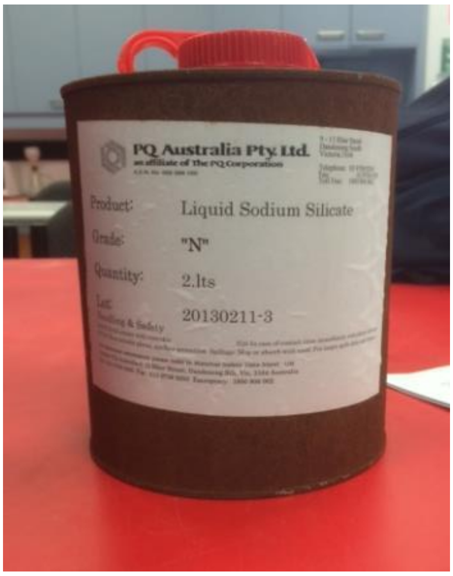


Figure 5-2 Sodium Silicate

After this, the sodium silicate solution was mixed with the appropriate water quantity. The sodium silicate used, as shown in Figure 5-2, was ‘N’ grade Liquid Sodium Silicate from PQ Corporation Australia. Once the sodium silicate solution was complete, it was added into the sodium hydroxide solution, along with the extra water required for the mix and left to cool down.

The next step was to gather all of the dry materials required for each mix. Each material was measured by weight on the electronic scales in the laboratory, as shown in Figure 5-3.

Figure 5-3 Measuring dry materials on electronic scales

Once the correct weight of each material was obtained it was placed into the cement mixer. All of the dry materials were then mixed together for one minute. After this, the alkaline mix and extra water were added to the cement mixer and mixed together until all of the dry materials were combined into the wet mixture. A slump test was performed after each material was completely mixed in accordance with AS 1012.3.1.

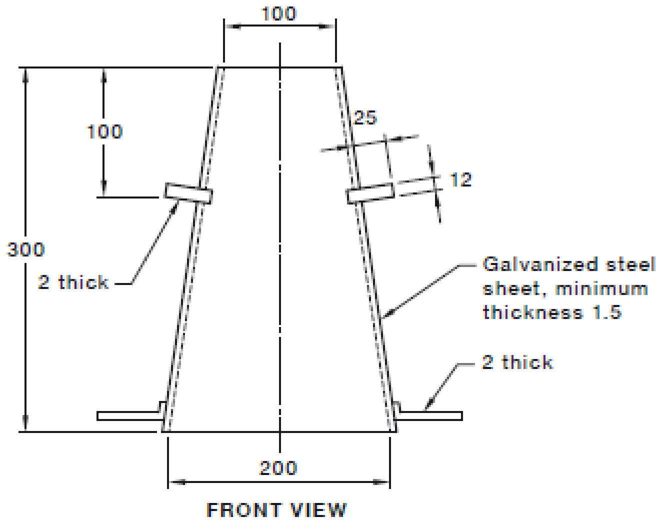


Figure 5-4 Slump Test Cone (AS1012.3.1)

The cone was filled in three equal layers with each layer rodded 25 times for compaction reasons. The slump for the Class F Fly Ash (FA) and Ground-granulated Blast-furnace Slag (GGBFS) mix was 160mm.

This slump value is very high in comparison to Ordinary Portland Cement (OPC) mixes but are fairly similar to that shown by Hardjito (2005).

After the slump test was performed, the mix was then placed into moulds. This was done so by filling the mould half way, rodding 25 times with an R24 bar, then filling to the top and rodding again 25 times. Figure 5-5 depicts the compaction by rodding with the R24 bar.

Figure 5-5 Compaction by rodding

In total, six moulds were created for FA & GGBFS. Of these six samples of FA & GGBFS, three will be tested at 7 days whilst the remaining three samples will be tested at 28 days.

Figure 5-6 Fly Ash and Ground-granulated Blast-furnace Slag Mix in Moulds

Once the mould was completely full, the top was finished with a small trowl and then placed into the curing room for 36 hours at 27° as per AS1012.8.1-2014. The samples were removed from the moulds after 24 hours, to free them up for other students. The samples were then placed back into the curing room for the rest of the 36 hour curing period. After the 36 hours had passed, the samples were removed from the curing room and left to cure at room temperature for the remainder of the waiting period until test day.

5.2 Testing Procedure

Seven days after the moulds were set, 3 cylinders of FA and GGBFS were tested for compressive strength in accordance with AS1012.9-2014 Methods of testing concrete, Method 9: Compressive strength tests. These tests were performed in lab Z1 at USQ's Toowoomba Campus on 2 September 2015.

Figure 5-7 Sample setup for Compressive Strength Test

Figure 5-7 shows the sample set into the machine ready for testing. The sample was locked in place with a rubber based cap which was placed on top of the sample. The cap then slotted into the machine's top plate and lowered into position so that the base was resting on the bottom plate. The impact machine was then set to apply a force equivalent to 20 +/- 2MPa compressive stress per minute until there is no more increase in force, as per AS 1012.9-2014. The maximum force applied to the sample was then noted from the display on the impact machine.

Of the three samples tested, it was noted that all samples fractured in a similar fashion. Figure 5-8 shows the elevation of the fractured sample with cracks running vertically towards the centroid of the sample. Figure 5-9 shows the plan view of the fractured sample with the crack running diagonally roughly through the centroid of the sample.

Figure 5-8 Fractured Sample after Testing

Figure 5-9 Plan view of the fractured sample

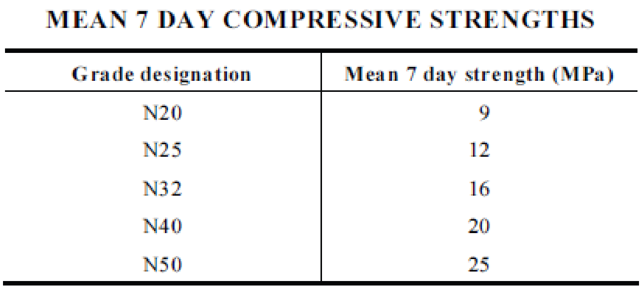
CHAPTER 6 RESULTS AND DISCUSSION

Table 6-1 Compressive Test Results at 7 days

Sample	type	Age Days	Initial Curing Hours	Ambient Curing Days	Height (mm)	Diameter (mm)	Force (kN)	Strength (MPa)
1	FA + GGBFS	7	28	6	200	100	111.7	14.2
2	FA + GGBFS	7	28	6	200	100	106.3	14.1
3	FA + GGBFS	7	28	6	200	100	106.1	14.1

The test results shown in Table 6-1 indicate a 7 day force required for fracture of the specimen of approximately 106kN. This would translate to a compressive strength of 14MPa. According to AS1379-2007 - Specification and supply of concrete, this would indicate a concrete grade of roughly 28MPa at 28 days, as shown in Table 6-2. This table is based on OPC and the results of the 28 day compression tests will be required to compare these values.

Table 6-2 Mean 7 day Compressive Strengths (AS1379-2007)



MEAN 7 DAY COMPRESSIVE STRENGTHS

Grade designation	Mean 7 day strength (MPa)
N20	9
N25	12
N32	16
N40	20
N50	25

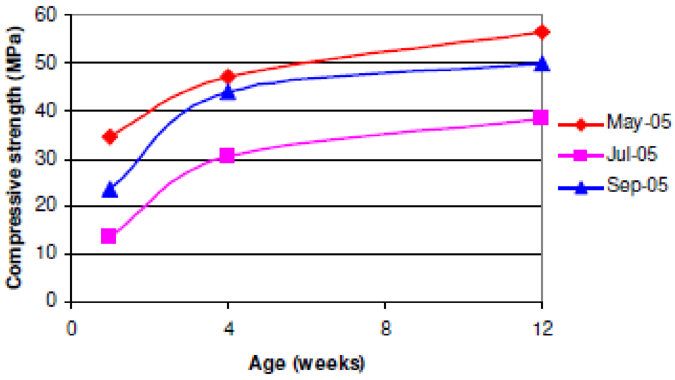


Figure 6-1 Compressive Strengths over time for curing at ambient conditions (Rangan 2006)

Rangan (2006), showed that samples cured at ambient conditions had slightly different development of strength over time. The following table shows the relationship depicted by Rangan (2006) for the three different GPC grades shown in Figure 6-1.

Table 6-3 Strength development relationship

Grade Designation	7 day Strength	28 day Strength	Relationship
N32	14	32	7 day = 0.4375 x Grade
N40	23	44	7 day = 0.575 x Grade
N50	35	48	7 day = 0.729 x Grade

It was noted, based on Table 6-2, that the samples may not reach the required 28 day compressive strength of 32MPa. Testing at 28 days will determine the accuracy of the mix design.

6.1 28 day test results

Table 6-4 Compressive Test Results at 28 days

Sample	type	Age Days	Initial Curing Hours	Ambient Curing Days	Height (mm)	Diameter (mm)	Force (kN)	Strength (MPa)
4	FA + GGBFS	28	28	6	200	100	121.8	15.51
5	FA + GGBFS	28	28	6	200	100	145.4	18.51
6	FA + GGBFS	28	28	6	200	100	131.3	16.72

The compressive test results shown in Table 6-4, are not reflective of the 7 day to 28 day strength development shown in either Table 6-2 or Figure 6-1. The 28 day strength is almost identical to that of the 7 day strength as shown in Table 6-1. This would indicate that the mix developed the maximum strength very early and will not increase greatly with time.

These results are obviously fair less than the 32MPa required for this mix, and as such, there are some possible reasons for the difference.

The sodium silicate solution quantities taken from the database were based on the sodium silicate being in powder form. This was then to be mixed with water to provide the solution. The sodium silicate available at the time of testing was in a solution form already. As such the water required to form the solution should have been removed from the mix. This would also reduce the W/GPS ratio as the silicate is not a solid and should therefore be left out of the geopolymer solids total.

The superplasticizer would have allowed greater workability of the mixture with a lowered water content.

As the ANNs were based on sodium silicate with water and superplasticizer, it would be suggested to use silicate powder and include superplasticizer for any future possible mixtures.

It was decided, even though there was not enough time to test, to revise the required materials for the Class F FA and GGBFS mix to see if a more appropriate mix could be found to provide a strength more closely to the 32MPa expected value. Upon review of Figure 4-6 - Class F Fly Ash and Ground-granulated Blast-furnace Slag - Alkaline/Binder Vs Water/Geopolymer Solids, it was decided to reduce the W/GPS ratio to 0.20.

Based on a W/GPS ratio of 0.20 for 6 cylinders and average percentages from the database:

- 55.9% water for hydroxide solution = 0.595L of water
- 57.9% water for silicate solution = 0.924L of water
- Extra Water = Approximately 0.04L
- Total water required = 1.56 litres

If pre-made sodium silicate solution was to be used, the water content of 0.924L for could be removed from the mix design. This would give a total water content of 0.636L. There is no doubt that the workability of this mix would be low and as such a superplasticizer would be required.

For the Superplasticizer, the super/binder ratio of 0.0025 will be used. Therefore, 0.02kg of Superplasticizer may be required.

The following table shows a revised summary of all materials required for the Class F fly ash and Ground-granulated Blast-furnace Slag test mix of 6-100mm diameter by 200mm high cylinders.

Table 6-5 Revised Class F Fly Ash and Ground-granulated Blast-furnace Slag Mix Design Summary

Fly Ash (kg)	Slag (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticiser (kg)
4.55	2.1	18.2	9.8	1.06	8M	0.595	1.596	0.924	0.04	0.02

CHAPTER 7 CONCLUSION

It is obvious that global warming has had an effect on the world climate over the last decade. And with this recognition, we must acknowledge that we have the power to help rectify the damage that mankind is causing to the planet. One way of reducing the greenhouse gas emissions is to develop alternate methods for the production of concrete. Geopolymer Concrete (GPC) is the method in our salvation. Of course it will not remove the damage already done but it will help reduce any further harm. If the technology and materials are available for use today, then it is the responsibility of all within the construction industry to use these materials. The government should set targets for greenhouse gas emission reductions and each manufacturer should be monitored and penalised for exceeding the limits.

It is not enough to say that it may cost a little more per cubic metre or may take a little longer to reach site. These issues should be taken into account at the start of the project and included in the cost and scheduling estimates before construction has begun.

By using the works developed in this project, society is well on the way to implementing a sustainable replacement for Ordinary Portland Cement (OPC).

7.1 Achievements

With the research data accumulated, there was enough information in the database to create Artificial Neural Networks (ANNs) and localise the ultimate mix of geopolymer materials to create a mix design that can be used in general construction.

The types of geopolymer concrete (GPC) focused on in this project were that based on Class F Fly Ash (FA), Class C FA, Ground-granulated Blast-furnace Slag (GGBFS) and that on Class F FA and GGBFS. From the ANNs created, it was possible to pinpoint a mix design for several standard grades of GPC.

The following tables represent the quantities of materials required for $1m^3$ of GPC based on the output of the ANN's. It must be noted that these mix designs have not been tested and should be treated as such.

Table 7-1 Material Quantities for $1m^3$ of Class F Fly Ash based Geopolymer Concrete

Grade	Fly Ash (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticizer (kg)
N20	400	1222	658	15-54	8-14	8-30	285-306	160-171	72-79	-
N25	400	1222	658	28-90	8-14	15-50	252-270	141-151	51-54	-
N32	400	1222	658	64-144	8-14	36-80	96	54	98-119	16-40
N40	400	1222	658	80-192	8-14	45-107	120-128	67-72	0	8-40
N50	400	1222	658	11-30	8-14	6-17	29-70	16-39	113-124	14-24

Table 7-2 Material Quantities for 1m3 of Class C Fly Ash based Geopolymer Concrete

Grade	Fly Ash (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticizer (kg)
N32	414	1091	588	85-108	13-15	47.5-60	103-127	59-74	15-37	26-41
N40	414	1091	588	84-107	12-14	47-60	102-125	59-72.5	14-35	21-41
N50	414	1091	588	83-106	11-12	46.5-59.3	101.5-124	59-72	13-32	10-19

Table 7-3 Material Quantities for 1m3 of Ground-granulated Blast-furnace Slag based Geopolymer Concrete

Grade	Slag (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)
N32	424	1072	575	54-95	13-15	30-53	41-81	24-47	165
N40	424	1072	575	64-113	12-14	36-63	48-97	28-56	163
N50	424	1072	575	71-125	11-12	40-70	53-107	31-62	162

Table 7-4 Material Quantities for 1m3 of Class F Fly Ash and Ground-granulated Blast-furnace Slag based Geopolymer Concrete

Grade	Fly Ash (kg)	Slag (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticizer (kg)
N32	320	80	1200	645	48-120	8-14	27-67	112-168	62-94	0-19	2
N40	320	80	1200	645	28-66	8-14	16-37	54-72	30-40	6-28	2
N50	320	80	1200	645	10-38	8-14	5-22	26-38	14-21	0-10	-

7.2 Future work

It is noted that the curing methods from the database were not all consistent or reflective of ambient conditions, which would be expected in real world applications. With this acknowledgement, it is advised that more testing be carried out based around ambient curing temperatures and then repeat the ANN process to pinpoint an ultimate mix for GPC.

As previously mentioned, the sodium silicate in the database and ANNs was based on the silicate as a powder and then mixed with water. To fully take advantage of the ANN results, it is suggested to use sodium silicate powder instead of pre-made sodium silicate solution. This would also ensure that the correct water content is used.

It would also be suggested that the revised mix design summary in Table 6-5 be tested first before proceeding onto other mix designs for testing purposes.

To fully cover the range of standard concrete grades, more testing of higher grades, i.e. 50MPa and above would need to be completed as well as more testing of slag only mixes and Class C FA mixes. This would overcome the inconsistencies with the ANN outputs due to lack of training data. It would then be advised to create ANNs again to determine the ultimate mix for each type of mixture. The quantities shown in Tables 7-1 to 7-4 would provide an excellent starting point for testing.

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Appendix A: Project Specification

University of Southern Queensland

FACULTY OF HEALTH, ENGINEERING & SCIENCES

ENG 4111/4112 Research Project

PROJECT SPECIFICATION

FOR: **AARON WILSON**

TOPIC: ESTABLISHING A MIX DESIGN PROCEDURE FOR GEOPOLYMER CONCRETE

SUPERVISOR: Dr Weena Lokuge, Lecturer in Civil Engineering

ENROLMENT: ENG 4111 – S1, 2015; ENG 4112 – S2, 2015

PROJECT AIM: This project seeks to analyse available data on geopolymer concrete mix design and through trending, establish a procedure by which geopolymer concrete can be mixed to produce a constant compressive strength similar to that currently available for Portland cement concrete.

PROGRAMME:

1) Research geopolymer mix designs to suit easily available materials used in the creation of geopolymer concrete.
2) Critically evaluate available data.
3) Establish database of collected quantities of materials and compressive strengths.
4) Review data and input into matlab to establish trends.
5) Produce mix design procedure that defines the necessary steps clearly and accurately.
6) Submit academic dissertation on the research.

As time permits:

7) Choose 2 mix designs relating to 32MPa concrete for testing.
8) Gather materials and mix concrete for testing.
9) Test samples and compare results to the gathered data.

AGREED Student: Aaron Wilson Date: 31/03/15

Supervisor: Weena Lokuge Date: 31/03/15

Examiner: Chris Snook

Appendix B: Database

Table B-0-1 Geopolymer Concrete based on Class F Fly Ash

Fly Ash (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticizer (kg)
476	1294	554	120	8M	71.52	48	26.832	0	0
350	1200	645	41	8M	28.823	103	57.1856	35	10.5
428	1170	630	57	14M	33.972	114	52.8618	86	4.3
400	950	850	57	12M	31.863	143	80.08	80	28
380	1050	800	40	8M	22.36	110	61.6	0	0
428	1170	630	57	14M	33.972	114	52.8618	64	4.3
400	1222	658	40	14M	23.84	100	58.5	0	6
408	1243	554	41	8M	24.436	103	45.423	20	0
400	1209	651	45.7	12M	25.5463	114.3	66.1797	0	0
400	1222	658	56	14M	33.376	84	49.14	0	6
408	1232	616	48	14M	28.608	103	57.577	0	0
428	1170	630	49	14M	29.204	122	56.5714	43	8.5
428.57	1177	623	68.57	14M	38.33	102.86	59.56	28.5	6.1
408	1246	554	41	8M	24.436	103	45.423	20	0
408	1080	554	41	8M	24.436	103	45.423	20	0
428	1170	630	49	14M	29.204	122	56.5714	43	17
394.29	1201	647	52.57	14M	29.39	105.14	60.8	21.4	6.1
428	1170	630	49	14M	29.204	122	56.5714	43	8.5
444	1170	630	44	14M	26.224	111	51.4707	43	9
428	1170	630	49	14M	29.204	122	56.5714	43	13
428	1170	630	57	14M	33.972	114	52.8618	43	4.3
408	1294	554	41	14M	24.436	103	57.577	21.3	8.2
408	1232	616	41	14M	24.436	103	57.577	21.3	8
408	1201	647	62	14M	36.952	93	57.66	4	0
428	1170	630	49	14M	29.204	122	56.5714	43	8.5
428	1170	630	49	14M	29.204	122	56.5714	43	8.5
428	1170	630	57	8M	33.972	114	52.8618	43	4.3
408	1243	554	41	8M	24.436	103	45.423	20	0
408	1232	616	55.4	8M	33.0184	103	57.577	0	6
420.57	1031.99	555.7	37.63	10M	22.4	80.126	39.3	113	8.41
378	1294	554	50	12M	26	124	69.316	0	8
378	1772	554	50	12M	26	124	69.316	0	8
408	1294	554	41	14M	24.436	103	57.577	10.7	8.2
408	1232	616	41	14M	24.436	103	57.577	10.6	8
428	1170	630	57	10M	33.972	114	52.8618	43	4.3
365.16	1117.99	602.04	34.30	10M	20.4445	73.04	35.8553	103	7.3
408.89	1177	623	57.24	14M	31.997	85.87	49.718	24.4	6.1

408	1294	554	51.5	14M	30.694	103	57.577	16.5	16.3
408	1294	554	41	14M	22.919	103	61.388	22.5	6
408	1201	647	62	14M	36.952	93	57.66	0	0
428	1170	630	49	14M	29.204	122	56.5714	43	8.5
408	1294	554	41	14M	24.436	103	57.577	22.5	6
254.54	1290	694.66	22.77	10M	13.5709	48.49	23.8037	68.7	5.1
408	1201	647	41	14M	24.436	103	57.577	20.7	6.1
406	1194	643	41	14M	24.436	102	57.018	26.8	6
404	1190	640	41	14M	24.436	102	57.018	25.5	6
480	1153	599	56	14M	31.304	112	64.848	23.7	6.1
400	950	850	57	12M	31.863	143	80.08	60	28
408	1201	647	41	12M	24.436	103	57.577	14.3	6.1
428	1170	630	57	14M	33.972	114	52.8618	43	4.3
444.44	1177	623	44.44	14M	24.8419	111.11	64.3327	18.6	6.1
498.46	1153	599	59.82	14M	33.439	89.72	51.9478	26.5	6.1
408	1201	647	41	12M	24.436	103	57.577	14.3	6.1
408	1201	647	41	14M	24.436	103	57.577	20.7	6.1
408	1201	647	41	16M	24.436	103	57.577	26.5	6.1
408	1294	554	41	14M	24.436	103	57.577	16.5	6.1
428	1170	630	57	14M	33.972	114	52.8618	43	8.5
408	1294	554	51.5	14M	30.694	103	57.577	16.5	4.1
408	1294	554	51.5	14M	30.694	103	57.577	16.5	8.2
408	1232	616	55.4	8M	33.0184	103	57.577	0	6
408	1294	554	51.5	14M	30.694	103	57.577	16.5	0
408	1201	647	41	12M	24.436	103	57.577	14.4	6.1
309.85	1204	648.35	27.73	10M	16.5270	59.03	28.97	83.6	6.2
408	1202	647	41	16M	24.436	103	57.577	26	6
461.54	1177	623	46.15	14M	25.7978	92.31	53.44	18.6	6.1
408	1201	647	41	14M	24.436	103	57.577	17.6	6.1
428	1170	630	57	12M	33.972	114	52.8618	43	4.3
408	1294	554	41	14M	24.436	103	57.577	0	8.2
408	1201	647	55.4	8M	33.0184	103	57.577	0	6.1
400	1265	540	42.3	16M	25.2108	105.7	59.086	24.3	4.2
400	950	850	57	12M	31.863	143	80.08	48	28
408	1201	647	41	10M	24.436	103	57.577	7.5	6.1
408	1232	616	41	14M	24.436	103	57.577	20.7	6
408	1232	616	41	14M	24.436	103	57.577	0	8
408	1294	554	41	14M	27.88	103	57.577	22.5	6
428	1170	630	49	14M	29.204	122	56.5714	43	8.5
408	1294	554	41	14M	24.436	103	57.577	22.5	6
400	950	850	57	12M	31.863	143	80.08	48	28
405	1235	545	52.9	16M	31.53	132.4	74.012	28	3
404	1190	640	41	14M	24.436	102	57.018	17	6
428	1170	630	57	14M	33.972	114	52.8618	43	4.3

428	1170	630	57	14M	33.972	114	52.8618	43	4.3
408	1201	647	41	8M	24.436	103	57.577	0	6.1
400	950	850	57	12M	31.863	143	80.08	48	28
476	1294	554	120	14M	71.52	48	26.832	0	0
408	1232	616	41	16M	24.436	103	57.577	26.5	6
350	1200	645	41	8M	28.823	103	57.1856	35	0
408	1201	647	68	14M	40.528	103	63.86	0	0
400	950	850	57	12M	31.863	144	81.0864	48	28
400	950	850	57	12M	31.863	143	80.08	48	28
380	1233	540	56.5	16M	33.674	141.3	78.99	14.6	4
428	1170	630	57	14M	33.972	114	52.8618	43	4.3
462.86	1153	599	52.9	14M	29.5711	132.24	76.56	21.2	6.1
404	1195	640	41	16M	24.436	102	57.018	20	6
408	1232	616	41	12M	24.436	103	57.577	14.4	6
408	1232	616	41	8M	24.436	103	57.577	0	6
400	950	850	57	12M	31.863	143	80.08	48	28
400	950	850	57	12M	31.863	143	80.08	48	28
400	950	850	57	12M	31.863	143	80.08	48	28
408	1232	616	41	10M	24.436	103	57.577	7.5	6
400	1356	535	51.5	16M	30.694	128.6	71.89	12.7	4.2
400	950	850	57	12M	31.863	143	80.08	40	28
408	1201	647	63	12M	32.76	138	77.142	0	8
408	723	647	63	12M	32.76	138	77.142	0	8
368	1294	554	53	8M	31.588	131	73.229	0	0
424.62	1177	623	36.4	14M	20.3476	90.99	52.68	15.9	6.1
408	1201	647	55.4	8M	33.0184	103	57.577	0	6.1
408	1232	616	41	8M	24.436	103	57.577	0	6
408	1294	554	41	8M	22.919	103	61.388	0	6
408	1294	554	41	8M	24.436	103	57.577	0	6
532.8	0	1600.8	41	8M	22.919	102.5	57.2975	0	0
476	1294	554	48	8M	28.608	120	67.08	0	0
408	1294	554	41	8M	27.88	103	57.577	0	6
408	1294	554	41	8M	24.436	103	57.577	0	6
408	1232	616	48	8M	28.608	103	57.577	0	0
408	1201	647	41	8M	24.436	103	57.577	0	6.1
404	1190	640	41	14M	24.436	102	57.018	16.5	6
408	1232	616	41	14M	24.436	103	57.577	0	8
476	1294	554	48	14M	28.608	120	67.08	0	0
408	1201	647	41	8M	24.436	103	57.577	0	6.1
420	1125	750	40		22.36	100	55.9	0	0
368	1294	554	53	8M	31.588	131	73.229	0	0
404	1190	640	41	14M	24.436	102	57.018	13.5	6
368	1294	554	53	8M	31.588	131	73.229	0	0
408	1201	647	41	14M	24.436	103	57.577	0	8.2

Table B-0-2 Geopolymer Concrete based Class C Fly Ash

Fly Ash (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticizer (kg)
503	0	1382	84.15	20M	47.04	170.85	99.26	34.17	60.31
503	0	1382	127.5	20M	71.27	127.50	74.08	34.17	40.20
503	0	1382	85	20M	47.52	170.00	98.77	34.17	50.25
414	1091	588	69	10M	41.12	138.00	71.50	0.00	0.00
503	0	1382	84.15	10M	47.04	170.85	99.26	0.00	0.00
414	1091	588	104	20M	61.98	104.00	53.88	0.00	0.00
503	0	1382	84.15	15M	47.04	170.85	99.26	17.09	15.08
414	1091	588	69	15M	41.12	138.00	71.50	0.00	0.00
414	1091	588	104	10M	61.98	104.00	53.88	0.00	0.00
503	0	1382	170	15M	95.03	85.00	49.39	22.61	30.15
503	0	1382	170	20M	95.03	85.00	49.39	39.70	50.25
503	0	1382	85	15M	47.52	170.00	98.77	17.09	25.13
503	0	1382	127.5	15M	71.27	127.50	74.08	17.09	20.10
414	1091	588	104	15M	61.98	104.00	53.88	0.00	0.00
414	1091	588	69	20M	41.12	138.00	71.50	0.00	0.00
503	0	1382	127.5	10M	71.27	127.50	74.08	0.00	0.00
503	0	1382	170	10M	95.03	85.00	49.39	11.56	15.08
503	0	1382	85	10M	47.52	170.00	98.77	0.00	0.00

Table B-0-3 Geopolymer Concrete based on Ground-granulated Blast-furnace Slag

Slag (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticizer (kg)
400	860	860	84	8M	46.96	28.00	15.68	156.0	0
400	844	844	76	8M	42.48	76.00	42.56	144.0	0
394.3	1232	616	131.4		73.45	26.30	12.10	67.60	0
424	1072	575	13	8M	7.27	46.50	26.04	216.0	0
424	1072	575	16.3	8M	9.11	58.10	32.54	212.0	0
424	1072	575	19.5	8M	10.90	69.70	39.03	208.0	0
380.7	1232	616	128.5		71.83	42.80	19.69	41.20	0
360	1264	632	108		60.37	36.00	16.56	58.80	0
336	1264	632	140		78.26	28.00	12.88	17.60	0
368	1232	616	92		51.43	92.00	42.32	58.80	0
428.6	1200	600	85.7		47.91	85.70	39.42	83.30	0
413.8	1200	600	155.2		86.76	31.00	14.26	47.00	0
400	1200	600	150		83.85	50.00	23.00	52.90	0
400	832	832	68	8M	38.01	120.00	67.20	132.0	0
347.6	1264	632	78.2		43.71	78.20	35.97	70.60	0

Table B-0-4 Geopolymer Concrete based on Class F Fly Ash and Ground-granulated Blast-furnace Slag

Fly Ash (kg)	Slag (kg)	Coarse Agg (kg)	Fine Sand (kg)	NaOH Mass (kg)	NaOH Molarity	Water in NaOH (kg)	Sodium Silicate (kg)	Water in Silicate (kg)	Extra Water (kg)	Super plasticizer (kg)
325.5	24.5	1200	645	41	8M	28.82	103.00	57.19	35	0
339.5	10.5	1200	645	41	8M	28.82	103.00	57.19	35	0
360	40	1216	655	40	14M	23.84	100.00	58.50	8	6
360	40	1216	655	56	14M	33.38	84.00	49.14	8	6
360	40	1209	651	51.5	12M	28.79	128.50	74.40	0	0
339.5	10.5	1200	645	41	8M	28.82	103.00	57.19	35	0
360	40	1209	651	45.7	12M	25.55	114.30	66.18	0	0
360	40	1209	651	53.3	12M	29.79	106.70	61.78	0	0
360	40	1209	651	64	12M	35.78	96.00	55.58	0	0
320	80	1216	655	40	14M	23.84	100.00	58.50	8	6
385	85	1300	550	0	12M	0.00	110.00	61.49	45	0
325.5	24.5	1200	645	41	8M	28.82	103.00	57.19	35	0
360	40	1209	651	45.7	14M	27.24	114.30	66.87	0	0
360	40	1209	651	64	14M	38.14	96.00	56.16	0	0
360	40	1209	651	40	12M	22.36	100.00	57.90	0	0
320	80	1216	655	56	14M	33.38	84.00	49.14	8	6
320	80	1209	651	45.7	12M	25.55	114.30	66.18	0	0
320	80	1209	651	45.7	14M	27.24	114.30	66.87	0	0
158.4	350.4	0	1524	41	8M	22.92	102.50	57.30	0	0
156	343.2	0	1502	41	8M	22.92	102.50	57.30	0	0
320	80	1209	651	64	14M	38.14	96.00	56.16	0	0
156	343.2	0	1500	41	8M	22.92	102.50	57.30	0	0
280	120	1209	651	45.7	12M	25.55	114.30	66.18	0	0
105.6	232.8	806.4	1032	41	8M	22.92	102.50	57.30	0	0
420	1125	0	750	40	12M	22.36	100.00	55.90	0	0

Appendix C: Artificial Neural Network Data

Table C-0-1 Class F Fly Ash Artificial Neural Network inputs, targets and predicted outputs

NaOH/ Sodium Silicate	AL/FA	W/GPS	Super/Binder	NaOH Molarity	Compressive Strength (MPa)	Predicted Compressive Strength
0.40	0.41	0.297	0.030	8	20	37.48716327
0.50	0.40	0.337	0.010	14	20	32.35372186
0.40	0.50	0.393	0.070	12	22.58	38.96193747
0.36	0.39	0.188	0.000	8	24	47.78985368
0.50	0.40	0.295	0.010	14	24	34.59840653
0.40	0.35	0.180	0.015	14	25	39.36794657
0.40	0.35	0.186	0.000	8	25	43.38942883
0.40	0.40	0.196	0.000	12	26	37.12317855
0.67	0.35	0.180	0.015	14	27	37.19333897
0.47	0.37	0.182	0.000	14	28	41.77777243
0.40	0.40	0.251	0.020	14	28	36.92748634
0.67	0.40	0.252	0.014	14	28.64	37.29445203
0.40	0.35	0.186	0.000	8	29	43.38942883
0.40	0.35	0.186	0.000	8	29	43.38942883
0.40	0.40	0.251	0.040	14	29	37.0594377
0.50	0.40	0.242	0.015	14	29.71	37.92312669
0.40	0.40	0.251	0.020	14	30	36.92748634
0.40	0.35	0.232	0.020	14	30	37.80030647
0.40	0.40	0.251	0.030	14	30	36.89654396
0.50	0.40	0.253	0.010	14	30	37.32609112
0.40	0.35	0.220	0.020	14	32	38.19369819
0.40	0.35	0.220	0.020	14	32	38.19369819
0.67	0.38	0.211	0.000	14	32	39.75294803
0.40	0.40	0.251	0.020	14	32	36.92748634
0.40	0.40	0.251	0.020	14	32	36.92748634
0.50	0.40	0.253	0.010	8	32	35.15739869
0.40	0.35	0.186	0.000	8	33	43.38942883
0.54	0.39	0.190	0.015	8	33	46.7163224
0.47	0.28	0.368	0.020	10	33.75	47.64114071
0.40	0.46	0.209	0.021	12	34.59	35.63436209
0.40	0.46	0.209	0.021	12	34.6	35.63436209
0.40	0.35	0.197	0.020	14	35	38.96583658
0.40	0.35	0.197	0.020	14	35	38.96583658
0.50	0.40	0.253	0.010	10	35	31.35315684
0.47	0.29	0.384	0.020	10	35.25	46.63194798
0.67	0.35	0.226	0.015	14	35.73	36.40944601
0.50	0.38	0.221	0.040	14	36	39.54479158
0.40	0.35	0.228	0.015	14	36	37.47689344
0.67	0.38	0.202	0.000	14	36	40.40615961

0.40	0.40	0.251	0.020	14	36	36.92748634
0.40	0.35	0.222	0.015	14	36	37.68865322
0.47	0.28	0.368	0.020	10	36.75	47.64114071
0.40	0.35	0.219	0.015	14	37	37.796155
0.40	0.35	0.232	0.015	14	37	37.33760238
0.40	0.35	0.230	0.015	14	37	37.40709146
0.50	0.35	0.217	0.013	14	37.09	37.32050817
0.40	0.50	0.352	0.070	12	37.31	39.99400481
0.40	0.35	0.205	0.015	12	38	34.80745995
0.50	0.40	0.253	0.010	14	38	37.32609112
0.40	0.35	0.211	0.014	14	38.69	38.01674644
0.67	0.30	0.199	0.012	14	39.93	29.79373755
0.40	0.35	0.205	0.015	12	40	34.80745995
0.40	0.35	0.219	0.015	14	40	37.796155
0.40	0.35	0.231	0.015	16	40	45.83729171
0.40	0.35	0.210	0.015	14	40	38.12710502
0.50	0.40	0.253	0.020	14	40	36.98795195
0.50	0.38	0.221	0.010	14	41	38.99187962
0.50	0.38	0.221	0.020	14	41	39.13584485
0.54	0.39	0.190	0.015	8	41.25	46.7163224
0.50	0.38	0.221	0.000	14	42	39.62596752
0.40	0.35	0.205	0.015	12	42	34.80745995
0.47	0.28	0.368	0.020	10	42	47.64114071
0.40	0.35	0.230	0.015	16	42	45.92672298
0.50	0.30	0.188	0.013	14	42.51	31.28817076
0.40	0.35	0.212	0.015	14	43	38.0523257
0.50	0.40	0.253	0.010	12	43	32.99430107
0.40	0.35	0.175	0.020	14	44	39.78826155
0.54	0.39	0.190	0.015	8	44	46.7163224
0.40	0.37	0.228	0.011	16	44	49.46895111
0.40	0.50	0.328	0.070	12	44.81	40.54382626
0.40	0.35	0.190	0.015	10	45	37.49384185
0.40	0.35	0.219	0.015	14	45	37.796155
0.40	0.35	0.175	0.020	14	45	39.78826155
0.40	0.35	0.231	0.015	14	45	37.37231075
0.40	0.40	0.251	0.020	14	45	36.92748634
0.40	0.35	0.222	0.015	14	45	37.68865322
0.40	0.50	0.328	0.070	12	45.01	40.54382626
0.40	0.46	0.268	0.007	16	46	47.27740674
0.40	0.35	0.211	0.015	14	46	38.08961922
0.50	0.40	0.253	0.010	14	46	37.32609112
0.50	0.40	0.253	0.010	14	46	37.32609112
0.40	0.35	0.175	0.015	8	47	52.1211135
0.40	0.50	0.328	0.070	12	47.99	40.54382626

2.50	0.35	0.180	0.000	14	48	24.55164467
0.40	0.35	0.231	0.015	16	48	45.83729171
0.40	0.41	0.297	0.000	8	48	29.97233033
0.66	0.42	0.220	0.000	14	48	42.04854653
0.50	0.50	0.330	0.070	12	48.53	37.97773728
0.40	0.50	0.328	0.070	12	48.56	40.54382626
0.40	0.52	0.230	0.011	16	49	53.82809172
0.50	0.40	0.253	0.010	14	49	37.32609112
0.40	0.40	0.235	0.013	14	49.64	38.46335485
0.40	0.35	0.218	0.015	16	50	46.9878921
0.40	0.35	0.205	0.015	12	51	34.80745995
0.40	0.35	0.175	0.015	8	51	52.1211135
0.40	0.50	0.328	0.070	12	51.03	40.54382626
0.40	0.50	0.328	0.070	12	51.41	40.54382626
0.40	0.50	0.328	0.070	12	51.68	40.54382626
0.40	0.35	0.190	0.015	10	52	37.49384185
0.40	0.45	0.266	0.011	16	52	46.85240604
0.40	0.50	0.311	0.070	12	53.46	40.99433246
0.46	0.49	0.220	0.020	12	54.2	33.14327641
0.46	0.49	0.220	0.020	12	54.2	33.14327641
0.40	0.50	0.234	0.000	8	54.66	40.47888148
0.40	0.30	0.186	0.014	14	54.89	32.37654495
0.54	0.39	0.190	0.015	8	55	46.7163224
0.40	0.35	0.175	0.015	8	55	52.1211135
0.40	0.35	0.180	0.015	8	56	51.37753295
0.40	0.35	0.175	0.015	8	56	52.1211135
0.40	0.27	0.135	0.000	8	56.5	34.38740485
0.40	0.35	0.175	0.000	8	57	45.12108091
0.40	0.35	0.183	0.015	8	58	50.93078163
0.40	0.35	0.175	0.015	8	58	52.1211135
0.47	0.37	0.182	0.000	8	60	44.09692945
0.40	0.35	0.175	0.015	8	63	52.1211135
0.40	0.35	0.210	0.015	14	66	38.12710502
0.40	0.35	0.175	0.020	14	66.75	39.78826155
0.40	0.35	0.175	0.000	14	68	39.63181908
0.40	0.35	0.175	0.015	8	68	52.1211135
0.40	0.33	0.162	0.000	8	70.5	44.45760151
0.40	0.50	0.234	0.000	8	71.59	40.47888148
0.40	0.35	0.204	0.015	14	76	38.35638372
0.40	0.50	0.234	0.000	8	85.66	40.47888148
0.40	0.35	0.175	0.020	14	89	39.78826155

Appendix D: Sample Matlab Plotfile

```
% Aaron Wilson Student Number 0050052015
%GGBFS Plot File.


%inputs
%NaOH/Sodium Silicate Ratio
NaS = slag_inputs(:,4)';
NaSnodes = 0.1:0.01:1;

%AL/Slag Ratio
ALslag = slag_inputs(:,5)';
ALslagnodes = 0:0.01:0.55;

%Water/Geopolymer Solids Ratio
WGPS = slag_inputs(:,6)';
WGPSnodes = 0.4:0.01:0.55;

%Outputs
z = ANN_slag_outputs';




%%
%Al/Slag Vs W/GPS

%fit data to surface
Z = gridfit(ALslag,WGPS,z,ALslagnodes,WGPSnodes);

%plot the file

figure
[A,b]= contourf(ALslagnodes,WGPSnodes,Z);
clabel(A,b)
title ('Ground Granulated Blast Furnace Slag - AL/Slag Vs
Water/Geopolymer Solids')
xlabel ('AL/Slag')
ylabel ('W/GPS')
print('slag - AL_Slag Vs W_GPS', '-djpeg', '-r300')
%%
%NaOh/Sodium Silicate Vs Al/Slag

%fit data to surface
Z2 = gridfit(NaS,ALslag,z,NaSnodes,ALslagnodes);

%plot the file

figure
[B,c]= contourf(NaSnodes,ALslagnodes,Z2);
clabel(B,c)
title ('Ground Granulated Blast Furnace Slag - NaOH/Sodium
Silicate Vs AL/Slag')
xlabel ('NaOH/Sodium Silicate')
ylabel ('AL/Slag')
print('slag - NaOH_Silic Vs AL_Slag', '-djpeg', '-r300')
%%
%NaOh/Sodium Silicate Vs W/GPS
```

```
Z3 = gridfit(NaS,WGPS,z,NaSnodes,WGPSnodes);

%plot the file

figure
[C,d]= contourf(NaSnodes,WGPSnodes,Z3);
clabel(C,d)
title ('Ground Granulated Blast Furnace Slag - NaOH/Sodium
Silicate Vs Water/Geopolymer Solids')
xlabel ('NaOH/Sodium Silicate')
ylabel ('W/GPS')
print('slag - NaOH_Silic Vs W_GPS', '-djpeg', '-r300')
```