University of Southern Queensland

Faculty of Health, Engineering and Sciences

Development of Low CO_2 Durable Concrete Using Geopolymer and Related Chemically-Activated Cements

Project Wang 92

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ABSTRACT

Concrete is a vital construction material in modern society as it is used to shape the built environment in many ways. Its use can be seen in the construction of road and rail infrastructure, buildings, dams, runways, and water and sewerage systems. It is the most widely used man-made material in the world.

Not to be confused with cement, concrete is essentially a mixture of aggregates and paste which are combined to form a solid, rock like mass. Aggregates are typically sand and gravel or crushed stone, and the paste is typically water and Portland cement (more commonly known as ordinary Portland cement (OPC).

There are many aspects of OPC concrete production that appear to be coming under increased scrutiny from an environmental and sustainability perspective. OPC concrete traditionally relies on the quarrying of non-renewable raw materials, and significant amounts of coal are used in the production of Portland cement. Electricity is needed to run the machinery for grinding, blending, and processing, and the concrete industry typically has high fuel use and a need for heavy transport in the supply and distribution chain. These factors mean that concrete production is commonly associated with the depletion of the world's natural resources and significant CO_2 emissions.

The increased awareness of environmental and sustainability issues in the concrete industry is leading to the development of new source materials for concrete production. Recent innovations in this area include the use of Portland cement-free, low CO_2 binders, commonly referred to as geopolymers binders, which result in concrete mixes (i.e. geopolymer concretes) with similar mechanical properties to OPC concrete, but which offer a lower carbon footprint.

Geopolymer concrete has garnered attention in recent years, mainly as a result of being more "environmentally friendly" than OPC concrete. Sometimes referred to as "green" or "low carbon" concrete, previous studies have proven geopolymer concretes to be environmentally superior through the use of binders manufactured from waste / industrial by-products (e.g. fly ash and blast furnace slag), rather than virgin raw materials extracted by quarrying.

Previous experimental work has shown that geopolymer concrete can offer similar mechanical properties to OPC concrete, with comparable compressive strengths, elastic moduli, and Poisson's ratio. In some instances, geopolymers can exhibit properties superior to OPC concrete, such as better heat resistance and low creep and drying shrinkage properties. Geopolymers can also offer enhanced resistance to many common concrete durability issues. With these factors in mind,

geopolymer concrete appears to offer many of the attributes of OPC concrete and should therefore be considered as a suitable replacement.

Despite the potential advantages of geopolymer concrete, widespread acceptance and increased commercial use appears to be a long way off. The construction industry is often cautious and safety conscious when it comes to embracing new building materials. A thorough and detailed understanding of a new material and how it will react in critical design conditions may often be required before widespread utilisation and acceptance will take place. In this regard, it was the intention that this research project would assist in advancing the geopolymer cause.

With this in mind, the main objective of this research project was to strengthen the position of geopolymer concrete via experimental investigations that helped gain a deeper understanding of how differing activator solution ratios and their concentration affect strength, along with different binder ratios. Different geopolymer concrete mix designs were developed to have a target compressive strength of 30MPa, with varying activator solution ratios and binder ratios. Several important mechanical properties for the different mix designs were established via experimental testing (e.g. compressive strength, stress / strain characteristics, and modulus of elasticity). It was found that the tested geopolymer mixes were comparable with OPC concrete mixes in this regard.

During this research project one potential drawback discovered early on was the fast setting time for the tested mix designs, samples hardening to an unworkable hardness within minutes, even when submerged in water.

results

During this project testing phase, some of the Compression results that did not fall into what was logical logically expected. Thus, there were no quantifiable results achieved and the findings to be presented. What did eventuate, using logic and the principle of differentiation, was to replace suspected corrupted data with predicted values and plot the hypothesized results. While not tangible they have resulted in a sound and intriguing hypothesis into a direct cause and effect ration for the change in modulus. Using data derived using this method, in the near future, it may be possible to predict the effect that changes to the modulus will have on different fly ash to blast furnace slag mix ratios.

Conclusion

While concrete results eluded the research project certain conclusions can be assumed, cursory evidence points to a direct relationship between the modulus and the compression strength of the casting. Currently, the data is insufficient to state this conclusively, but initial data indurates this to be the case.

Industry acceptance and widespread use of fly-ash/slag based geopolymer concrete, as an alternative building material, is still some time away. At this stage of understanding, there are still too many unknowns and potential complications that need to investigated and rectified. However, fly ash/slag based Geopolymer concrete has demonstrated that it has exciting potential within the construction industry when these challenges are overcome.

DECLARATION

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NOMENCLATURE

Aerated concrete (AAC)

AAC is made with fine aggregates, cement, and an expansion agent that causes the fresh mixture to rise like bread dough. This type of concrete contains 80 percent air.

Alkali activated material (AAM)

AAM is a broad classification that encompasses essentially any binder system derived by the reaction of an alkaline salt (solid or dissolved) with a solid silicate powder.

Blast Furnace

A blast furnace is a huge steel stack lined with refractory brick, that is used in steel manufacturing. Iron ore, coke, and limestone are dumped into the top and preheated air is blown into the bottom, such that various chemical reactions take place as the material moves downwards. The end products are commonly molten metal and slag.

Calcined

Calcined is the term used to describe heating a substance to high temperature to cause loss of moisture, reduction or oxidation, and the decomposition of carbonates or other compounds. The substance is not heated above melting point.

Commonwealth of Independent States (CIS)

The CIS formed when the former Soviet Union (now Russia) dissolved in 1991.

Coalescence

Coalescence is the joining of two or more bubbles in the foam. Because larger bubbles have a tendency to rise to the surface, coalescence can lead to segregation and reduced strength.

Dissolution Process

The dissolving of gases, liquids, or solids into a liquid or other solvent is a process by which these original states become solutes (dissolved components), forming a solution of the gas, liquid, or solid in the original solvent.

Fly Ash (FA)

FA (also known as pulverised fuel ash) is a coal combustion by-product typically produced in coal fired power stations. It is a fine grey powder consisting mostly of spherical glassy particles.

Geopolymer

A geopolymer is a type of inorganic polymer that can be formed at room temperature by using industrial waste or by-products as source materials to form a solid binder that looks like and performs a similar function to Ordinary Portland Cement (OPC). Geopolymer can be used in applications to fully or partially replace OPC, and can offer enhanced environmental and technical benefits, including an 80-90% reduction in CO2 emissions, and improved resistance to fire and aggressive chemicals.

Hydration Process

The hydration process is a chemical reaction in which a substance combines with water. Within the context of concrete technology, as the reaction proceeds, the products of the hydration process gradually bond together sand and gravel particles (and other components), to form a solid mass.

Lineal
Lineal is flow in a direct line from a parent or parent group to the next in line.

Polycondensation
Polycondensation is any condensation reaction, of a monomer having two functional groups, which leads to the formation of a polymer.

Ordinary Portland Cement (OPC)
OPC is typically a dark grey nodular material which is made by heating ground limestone and clay at a temperature of about 1400-1500 °C. The nodules are ground up to a fine powder to produce cement, with a small amount of gypsum added to control the setting properties.

Pozzolan
Pozzolan is a siliceous or siliceous and aluminous material, which in itself possesses little or no cementing property, but will in a finely divided form, and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Sealed curing
Sealed curing is a method whereby the moisture which is present at commencement of the manufacturing process is retained through the use of an air and watertight film.

Segregation
Within the context of concrete technology, segregation is the process in which the ingredients (particles) separate from each other on account of variations in size, density and shape. For OPC, the coarse aggregate can separate out or settling down from rest of the matrix (Type 1 segregation). The paste can separate away from the course aggregate (Type 2 segregation). Water can also separate out (bleed) from the rest of the material (Type 3 segregation).

Silica fume
Silica fume is a by-product of silicon metal or ferrosilicon alloys, and its use in concrete technology can be very beneficial. The chemical and physical properties of silica fume make it a very reactive pozzolan. Concrete containing silica fume can have very high strength, and can be very durable.

Slag
Slag is a stony waste matter that is separated from metals during the smelting or refining of ore.

Surface saturated dry condition (SSD)
SSD is the condition where an aggregate in which the surfaces of the particles are "dry" (i.e., surface adsorption would no longer take place), but the inter-particle voids are saturated with water.

Sodium Hydroxide (NaOH)
NaOH (also known as lye and caustic soda) is an inorganic compound consisting of sodium cations and hydroxide anions.

Sodium Silicate (Na2SiO3)
Na2SiO3 (also known as water glass or liquid glass) is an inorganic compound that is available in aqueous solution and in solid form.

Surfactant
A surfactant is a material that affects the properties of an interface between air and liquid such that it provides a thermodynamically stable environment for foam.

1. INTRODUCTION

1.1 General

1.1.1 Current Concrete Technology (OPC Concrete)

Concrete is a vital construction material in modern society as it is used to shape the built environment in many ways. Its use can be seen in the construction of road and rail infrastructure, buildings, dams, runways, and water and sewerage systems. It is the most widely used man-made material in the world.

Not to be confused with cement, concrete is essentially a mixture of aggregates and paste which are combined to form a solid, rock like mass. Aggregates are typically sand and gravel or crushed stone, and the paste is typically water and Portland cement.

Portland cement, also commonly termed ordinary Portland cement (OPC), is a generic term used to describe the cement that is normally present in virtually all concrete used in construction around the world today. It appears as a fine powder and is typically produced by heating limestone and clay minerals to form clinker. The clinker is then ground and small amounts of other materials (e.g. calcium sulfate) are added to form the finished cement powder.

Concretes that contain Portland cement are called OPC concretes. In a typical OPC concrete, the cement is the binding agent and normally comprises 10-15% of the concrete mix by volume. It is the most active component and usually the most costly. Through a process called hydration, the cement and a portion of the water chemically react and give off heat, and it is this process that causes the concrete to solidify.

1.1.2 Issues with the OPC Concrete

There are many aspects of OPC concrete production that appear to be coming under increased scrutiny from an environmental and sustainability perspective. OPC concrete traditionally relies on the quarrying of non-renewable raw materials, and significant amounts of coal are used in the production of Portland cement. Electricity is needed to run the machinery for grinding, blending, and processing, and the concrete industry typically has high fuel use and a need for heavy transport in the supply and distribution chain. These factors mean that concrete production is commonly associated with the depletion of the world’s natural resources and significant CO_2 emissions.

1.1.3 Recent Developments in Concrete Technology

The increased awareness of environmental and sustainability issues in the concrete industry is leading to the development of new source materials for concrete production. For example, the depletion of natural sands typically used as aggregates has resulted in the development of concretes that utilise crumbed rubber replacements.

Another example of recent innovations, and the focus of this research project, is the use of Portland cement-free, low CO_2 binders, commonly referred to as geopolymers binders, which result in concrete mixes (i.e. geopolymer concretes) with similar mechanical properties to OPC concrete, but which offer a lower carbon footprint.

1.2 A Brief History of OPC Concrete

Concrete has been a staple construction material for a significant period of human history. The first recorded use was by the Egyptians (circa 3000 BC) who developed a gypsum based mortar for use in the construction of many of their structures (Winter 2012). Over 2000 years later, the ancient Romans developed a material with many similarities to modern concrete, incorporating heated limestone and fire ash, mixed with sand aggregates, which formed a product many view as the first "true concrete". The Romans recognised the potential of concrete as a construction material, and were responsible for many technological advances such as the addition of volcanic ash with heated lime to form a mix capable of curing under water (Winter 2012).

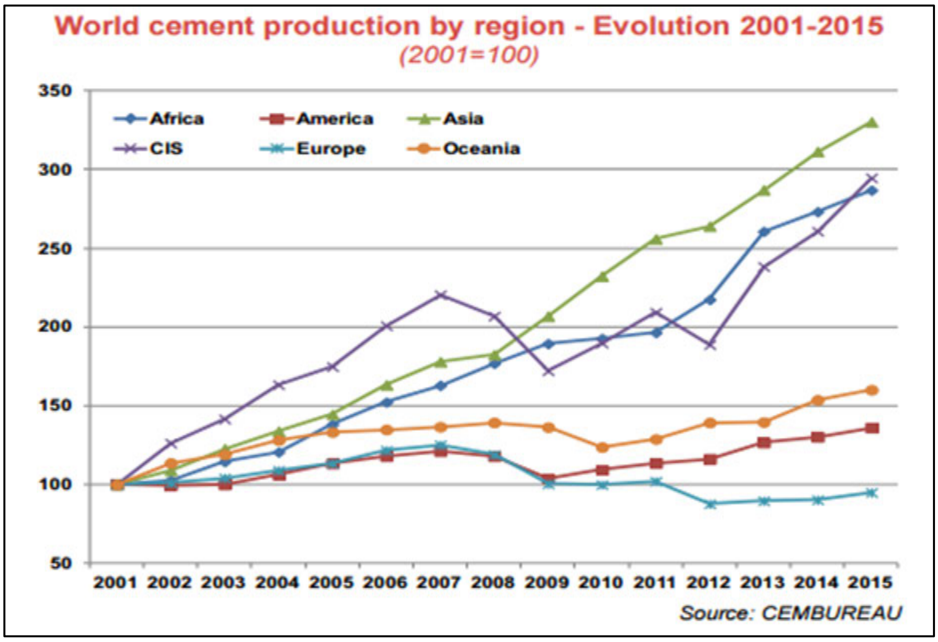
After Roman innovations, a significant period of time elapsed before any real advances in concrete technology occurred. It wasn't until 1824, through the work of Joseph Aspdin and his focus on improving the binding characteristics of the concrete ingredients, that the next significant steps were taken. Aspdin patented a low temperature fired compound comprising finely ground clay and limestone, whereby the limestone was heated until it calcined. His product is regarded by many as the world's first introduction to Portland cement. As a consequence, Aspdin (along with his son William) has become synonymous with Portland cement, after electing to name his product "Portland" on account of its similarity to a stone which was quarried on the Isle of Portland in Dorset.

Approximately 20 years later, Isaac Johnson, building on Aspdin's work, developed a process that utilized high temperatures (1400-1500^{o}C) when firing the lime, and in so doing created the forerunner of modern (ordinary) Portland cement (OPC), which to this day incorporates firing temperatures of this magnitude in the OPC production.

Since its invention, OPC concrete has become the most widely used construction material in the world (Juenger, 2011; Palomo. 1999; Damtoft. 2008; Da-Hai Yan. 2010; Bolt. 2013; van Deventer. 2010). This is largely due its relatively low cost and widespread availability, versatility, durability and reliability. In recent times, OPC concrete production has grown significantly, most notably in developing regions such as Asia, Africa, and The Commonwealth of Independent States (CIS) in Russia (Cembureau 2015).

1.3 The Need for Alternatives to OPC Concrete

An increased awareness of the depletion of natural resources and the creation of CO_2, both part and parcel of the manufacturing process for OPC concrete, is leading to the need for more sustainable materials and technologies. In addition, the recent modernisation and industrialisation experienced in high population nations such as India and China (Van Deventer et al. 2012) has significantly increased the demand for building materials, which places further strain on the natural resources used in concrete production. To demonstrate this point, the figure below, from the European Cement Organisation 2015 Annual Report, illustrates the sharp increase in cement production from 2001 to 2015 in Africa, Asia, and the CIS regions.



World cement production by region - Evolution 2001-2015

(2001=100)

Source: CEMBUREAU

Figure 1.3.1; World Cement Production by Region 2001-2015

With regards to CO_2 emissions and global warming, or more specifically, man-made climate change, CO_2 has been identified by some researchers as the primary contributor (Mehta 2010a; Purnell 2012). The worldwide cement industry, which produced 4,300 million tons in 2016 according to US world cement statistics, is reportedly responsible for between 5 to 8% of the world’s total global CO_2 emissions, with 90% of those figures generated from the production of Portland clinker (Van Deventer, 2012).

Whilst the debate on whether man-made climate change science is “settled” or not continues, the increase in demand for lime for cement production in some counties will soon exceed supply capabilities, and this in itself provides suitable justification for investing in alternative source materials. In China alone, and based on the 2008 mined consumption rate of 56 million tons, current estimates predict limestone reserves will be exhausted by 2062 (Schneider, 2011).

1.4 Introduction to Geopolymer Concrete

Geopolymer concrete has garnered attention in recent years, mainly as a result of being more “environmentally friendly” than OPC concrete. Sometimes referred to as “green” or “low carbon” concrete, previous studies have proven geopolymer concretes to be environmentally superior through the use of binders manufactured from waste / industrial by-products (e.g. fly ash and blast furnace slag), rather than virgin raw materials extracted by quarrying.

The main materials required in the production of geopolymer concrete are:

- Fly ash (a geopolymeric source material / binder and a by-product of coal fired power plants);
- Blast furnace slag (a geopolymeric source material / binder and a by-product of steel production);
- Alkaline activator solution to activate the geopolymeric source materials;
- Fine and course aggregates as required for OPC concretes.

Unlike OPC mixes, concrete manufactured with geopolymer binders do not require heat and do not produce CO_2. It is also important to recognize that, although present in the activator solution, water does not play a part in the chemical reaction that leads to the hardening and solidification of geopolymer concrete. This is in contrast to OPC concretes, which require water to create the necessary chemical reaction which leads to hardening. Synthesis of a geopolymer usually involves mixing the geoplymeric source materials with an activator solution.

1.5 Geopolymer Concrete as a Replacement to OPC Concrete

Experimental work has shown that geopolymer concrete can offer similar mechanical properties to OPC concrete, with comparable compressive strengths, elastic moduli, and Poisson’s ratio. In some instances, geopolymers can exhibit properties superior to OPC concrete, such as better heat resistance and low creep and drying shrinkage properties. Geopolymers can also offer enhanced resistance to many common concrete durability issues. With these factors in mind, geopolymer concrete appears to offer many of the attributes of OPC concrete and should therefore be considered as a suitable replacement.

1.6 The Challenges for Geopolymer Concrete

Despite the potential advantages of geopolymer concrete, widespread acceptance and increased commercial use appears to be a long way off. The construction industry is often cautious and safety conscious when it comes to embracing new building materials. A thorough and detailed understanding of a new material and how it will react in critical design conditions may often be required before widespread utilisation and acceptance will take place. In this regard, it is the intention that this research project will assist in advancing the geopolymer cause.

1.7 Project Objectives

Sustainability is defined as "the ability to meet our current needs without compromising the ability of future generations to meet theirs" (C.A. Hendriks, 1998; Worrell. E, 1993).

Whether or not a nation or an individual believes in man-made climate change, the reduction of CO_2 emissions via a reduced dependency on Portland cement can only be viewed as a positive outcome if it reduces the impact on future generations. Similarly, a reduced dependency on OPC concrete will also ensure that current rates of raw material depletion are slowed.

There appears to be a genuine desire for change, with many designers and suppliers keen to use OPC alternatives, however, whilst the advantages of reduced OPC dependency are clear, it is apparent that a number of significant hurdles must be overcome in order to gain global acceptance of potentially suitable alternatives, such as geopolymers.

With this in mind, the main objective of this research project is to strengthen the position of geopolymer concrete via experimental investigations that will lead to a deeper understanding of how differing activator solution ratios and their concentration affect strength, along with different binder ratios.

In order to fulfil this objective, the following tasks will be undertaken:

- Develop geopolymer concrete mix designs that have a target compressive strength of 30MPa, whilst varying the activator solution ratios and binder content;
- Determine several important mechanical properties for the different mix designs via experimental testing (e.g. compressive strength, stress / strain characteristics, and modulus of elasticity);
- Compare and contrast the results from the different mix designs to identify trends, determine if predictable results can be obtained, and determine the effect of different activator ratios / binder ratios.

2. REVIEW OF GEOPOLYMER CONCRETE

2.1 Background

Alkali activated materials such as geopolymer concrete are alternative building materials that can be manufactured using fly ash or granulated blast furnace slag. The “right” combination will create a strong and durable construction material.

The combination of fly ash, granulated blast furnace slag, and an alkaline activator produces a material with short chain simple molecules which, while providing a strong material, results a susceptibility to chemical break down not found with long chain complex molecules. The stability and durability of these compounds can be altered (for the better) with the addition of a binding agent that changes the short chain molecules into complex long chain molecules, thereby creating what is commonly classified as a geopolymer concrete.

In 1977 Davidovits introduced the world to the term geopolymers, which he reported were are amorphous, without clearly defined form or shape, and exhibits ceramic-like properties. He also reported that silicates and alumina are the main contents and are used to produce a binder-like structure through using the polymerization of high alkalinity solutions (Hardjito 2005).

2.2 Source Materials for Geopolymer Concrete

2.2.1 Fly Ash

Fly ash (or more specifically coal fly ash) is the waste by-product of power generation in coal-fired power stations. It is similar in appearance to Portland cement, as is evident in the figure below.

Figure 2.2.2; Portland Cement versus Fly Ash (visual Similarities')

After the fuel coal has been combusted in the power station boiler, the residual materials bind together to form glassy spheres of alumina-silicate. While the fly ash looks like a fine powder to the naked eye, under magnification the glass bead-like nature is revealed, as is evident in the figure below.

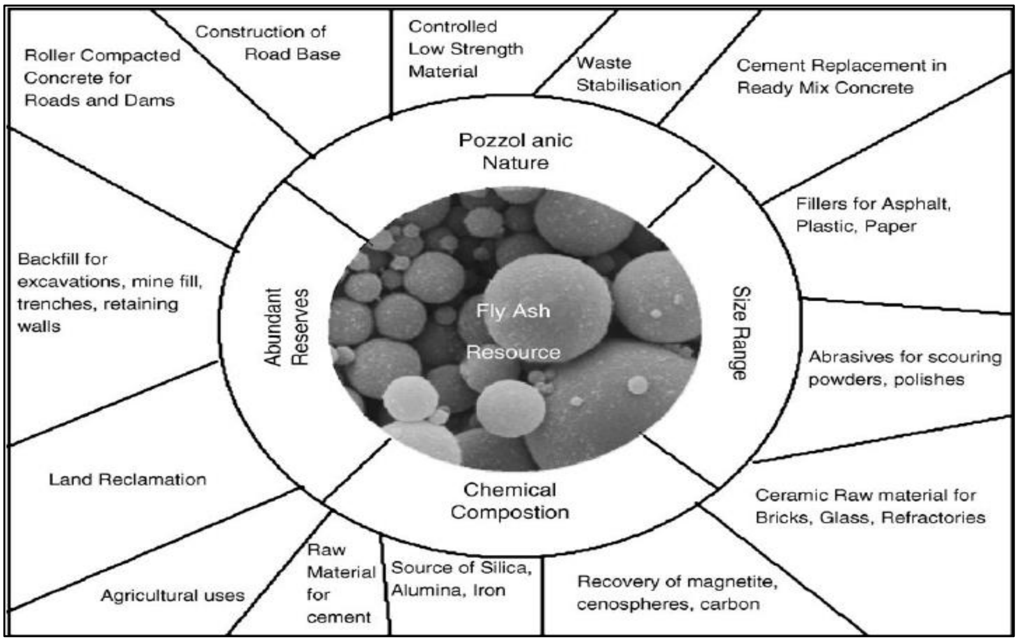


Figure 2.2.3; Electron Microscope Image (EMI) of Fly Ash

In Australia, fly ash is most commonly sourced from coal-fired power stations, with Gladstone Power Station considered the best source for geopolymers. This is due to the fly ash having consistent qualities and reliable results (Riessen and Tan, 2013; Temuujin, Rickard and Riessen, 2013; Tennakoon, 2014). Gladstone generates 1680 Mega Watts, which is approximately 15% of Queensland's electricity demand (CS Energy, 2017). This is achieved by burning 11,000 tonnes of coal daily (over 4 million tonnes annually), which results in significant amounts of fly ash that require re-purposing or recycling.

The burning of the harder, older anthracite, and bituminous coal (black coal), typically produces Class F fly ash, which is pozzolanic in nature, and contains less than 7% lime (CaO). Possessing pozzolanic properties, the glassy silica and alumina of Class F fly ash require a cementing agent, such as quicklime, Portland cement, or hydrated lime, (mixed with water to react and produce cementitious like compound). Alternatively, by the addition of a chemical activator such as sodium silicate (water glass), Class F fly ash can be used to form a geopolymer.

The burning of younger younger lignite or sub-bituminous coal typically produces Class C fly ash. In addition to having pozzolanic properties, it can also exhibit some self-cementing properties. In the presence of water, Class C fly ash will harden and become stronger over a longer cure time. It typically contains more than 20% lime (CaO), and unlike Class F, self-cementing Class C fly ash does not require an activator. Alkali and sulphate (SO4) contents are typically in Class C fly ashes.

2.2.2 Blast Furnace Slag

Blast furnace slag (also known as ground granulated blast furnace slag, or GGBS) is another industrial waste byproduct, formed during the manufacturing of steel and iron. It is produced by the quenching of molten iron slag, a by-product of the smelting process, and produces a granulated product that is then dried and ground into a fine powder (Cement Australia, 2017).

When iron ore, coke and flux, (either dolomite or limestone), are melted together in a blast furnace, the lime in the flux chemically combines with the impurities, (aluminates and silicates of the iron ore and coke ash), to produce blast furnace slag. When the slag is rapidly quenched (cooled), with the use of large quantities of water, it produces sand like granules which are then ground for use in cement mixtures. If the slag is allowed to air cool slowly, it will form into larger granules. (Cheng and Chiu, 2003; Cheng and Hua, 2013).

Blast furnace slag is usually added to geopolymer concrete in ranges from 10-80 kg per cubic meter of geopolymer cement, in combination with fly ash.

While there are alternatives to blast furnace slag and fly ash in geopolymer manufacture, such as Kaolinite and red mud, they have not been considered a serious replacement material in an industrial application.

2.2.3 Alkali Activators

To produce stability in the alkali-activated material and turn it into a geopolymer an alkali solution or a binding agent must be added (Cembureau, 2015; Davidovits, 2015). There are many binding agents, however, in the context of this research project, only sodium silicate and sodium hydroxide will be examined. This is due to their low cost and availability.

These binder chemicals are combined as dry chemicals, allowing for easy and full mixing and dissolved in water, usually for 2-3 days, to obtain specific concentrations. When added to fly ash or blast furnace slag they supply the necessary elements to change the existing short chain molecules into long complex molecules, resulting in the concrete achieving the strength and durability needed for a range of construction projects and applications.

Further details for sodium silicate and sodium hydroxide (along with other activator solutions) are now provided:

- Sodium silicate (Na2SiO3), also known as water glass or liquid glass, is already a common additive within in the cement industry as a passive fire additive;
- Sodium hydroxide (NaOH), also known as lye and caustic soda, is an inorganic compound. It is a white solid and highly caustic metallic base and alkali of sodium which is available in pellets, flakes, granules. While this activator is effective in the right applications, it is most often only used as a secondary binder due to its high cost and scarcity (Provis. 2015);
- Potassium hydroxide (KOH) is an inorganic compound commonly called caustic potash. Along with sodium hydroxide, this colorless solid is a prototypical strong base;
- Potassium silicate (K2SiO3) is used to make a highly acid resistant concrete.

2.3 Geopolymer Reaction Mechanisms

The mechanism involved in the production of geopolymer can be categorized into the three main stages described below (Davidovits, 2008).

1. Dissolution of silica and alumina from the aluminosilicate source;
2. Reorganisation;
3. Polycondensation to form three-dimensional polymer chains.

It is important to emphasize again that water does not play a part chemical reaction during geopolymerisation. It only acts as transporting medium for the dissolved aluminate and silicate (Komljenovi, Bascarevi & Bradic, 2010).

Duxton (2007) presented a simplified conceptual flow diagram of the reaction mechanism for geo-polymerisation, (based on the Gluhhovsky model), which outlined the key processes that occur during the transformation to a geopolymer. This has been reproduced in figure below.

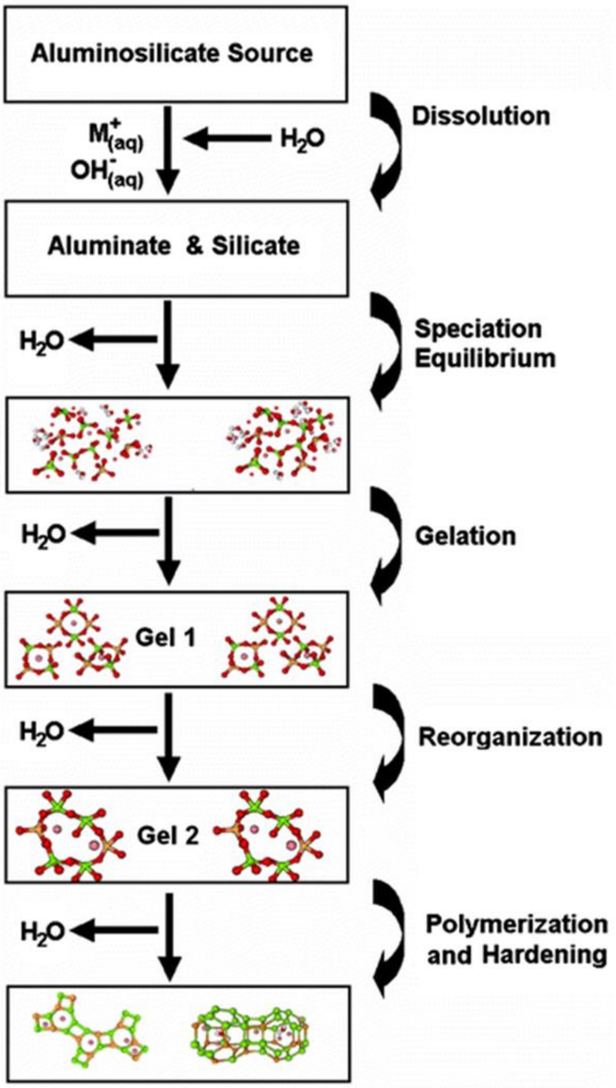


Figure 2.3.4; Reaction Mechanism for Geopolymer Concrete

Figure 2.3.1. Reaction Mechanism for Geopolymer Concrete

While Duxton presented the different stages in a lineal form, the processes usually happen simultaneously and / or concurrently. Dissolving of the solid aluminosilicate source in water produces aluminate and silicate. From this, a complex mixture of silicate, aluminate and aluminosilicate species is formed, and the speciation equilibrium in concentrated solutions results in the formation of a gel.

After gelation begins, the compound continues to reorganize and rearrange. The connectivity of the gel compound increases and results in the three-dimensional aluminosilicate network, typically attributed to geopolymer.

During the final stage, the nuclei reach a critical size and crystals begin to develop. These processes of structural reorganization are the major factor in determining the microstructure and pore distribution of the material, which is critical in determining many physical properties (Duxton, 2006).

2.4 Geopolymer Mechanical Properties

Experimentation has shown that geopolymer concrete has many promising and comparable properties to OPC concrete. The compressive strength is a key characteristic in any type of concrete, and studies have shown similar results between OPC concrete and geopolymer mixes. Much experimentation has been done to investigate the properties and characteristics of geopolymer concrete, some of which are expanded on in the following sections.

2.4.1 Heat Resistance

In 1989 Davidovits showed that geopolymer cement tends to exhibit heat resistant properties superior to OPC. The primary reason for this is that it is derived from a polycondensation process and not from a hydration process. Hydrated concrete has a tendency towards explosive cracking when exposed to extreme heat in excess of 800ºC (Davidovits 2013). It should be noted that this is more extreme when a low calcium binder is used.

2.4.2 Low Creep and Drying Shrinkage

In 2006, studies by Wallah showed that that geopolymer concrete samples undergo low creep and low drying shrinkage. In a year-long study, results showed that geopolymer cement experienced lower creep than OPC samples over the same period. Whilst the research illustrated a trend, the limited number of samples used does not give irrefutable results, and more testing with larger sample batches and a wider range of mixes needs to be completed.

2.4.3 Stress-Strain Relationship and Modulus of Elasticity

Testing has shown that geopolymer concrete demonstrates results similar to OPC on both the ascending and descending parts of the stress-strain curve (Hardjuito, 2005). The stress-strain curve of geopolymer concrete closely follows the predictive curve that was originally developed for OPC concrete. Hardito’s results suggest that some of the provisions already within current concrete standards for OPC may be used for geopolymer concrete. Joseph and Mathew (2012) achieved similar results when testing fly ash based geopolymer concrete, but also discovered that this could be improved with a better selection of course aggregates and combined with optimum fine aggregates.

2.4.4 Compressive Strength

Many researchers have shown that geopolymer can achieve higher compressive strength when cured by heat activation or by ambient curing (Hardjito 2005, Nath and sarker 2012). While heat curing will achieve higher compressive strengths, suitable results are also possible with ambient curing, on the condition that blast furnace slag is added to the matrix.

2.5 Factors Affecting Geopolymer Mechanical Properties

Where OPC compressive strength is almost exclusively governed by the binder water ratio (water / cement ratio), many factors can affect the compressive strength of Geopolymer cement. Some of these are expanded on in the following sections.

2.5.1 Curing temperature

The geopolymerisation process is accelerated when curing temperature is increased, resulting in a more efficient dissolution process. Hardjito and Rangan (2005) found that by raising the curing temperature, the compressive strength could be increased, but no significant improvement is achieved at temperatures over 70^{o}C. They also found that the best compressive results were achieved over the first 24-48 hours of heat curing.

2.5.2 Effect of water content

While water itself does not play a part in the geopolymerization process, the initial properties of the mixture do affect the properties of the geopolymer concrete. The water content is taken as a mass of water to be added to the hydrogen solution. The geopolymer solids are taken as the mass of the fly ash and the mass of blast furnace slag, added to the mass of sodium hydroxide and sodium silicate solids dissolved in water). Provis (2009) found that the compressive strength of the geopolymer concrete decreased as the water to solid ratio increased, but the workability of the mixture increases.

2.5.3 Addition of slag to the matrix

The compressive strength of a geopolymer mix can be increased with the addition blast furnace slag into the matrix. However, the higher the fly ash to slag ratio, the quicker the setting time of the mixture at ambient temperature (Davidovits 2011)

2.6 Aggregates

Like Portland cement, aggregates make up the largest proportion of volume in geopolymer concrete, and these ratios may vary depending on the intended use. A general industry standard mix for Portland cement is one (1) part ccement to two (2) parts sand or fine aggregates to three (3) parts course aggregates, or approximately 80% aggregate to 20% cement by mass.

Both the fine and coarse aggregate currently in use by the concrete industry have been found to be suitable for use in Geopolymer cement (Hardjitto, 2005). Research into aggregates for use in geopolymer concrete has been carried out with the aggregates prepared to a surface saturated dry condition (SSD), which is crucial when working with geopolymers because the aggregates must not be capable of absorbing any further moisture from the alkaline solution.

While the Australian Standard for Concrete (AS 2758.1 - 2014) has not caught up with the technology for geopolymer concrete, the recommendation is that the aggregate content is blended in the same mix ratios as for OPC concrete.

3. METHODOLOGY AND MATERIALS

3.1 Methodology

3.1.1 Preliminary Research

The first stage of the project was to research background material relating to the use of alkali-activated fly ash/slag cement, with a view to understanding the effects of differing mixes on compressive strength. The research examined differing testing methods, and involved familiarisation with the relevant standards. This enable the scope of the work to be determined.

3.1.2 Planning

At the onset of the project, it was established that two different binder ratios should be investigated; 80% FA : 20% GGBS & 70% FA : 30% GGBS (where FA = fly ash and GGBS = ground granulated blast furnace slag). These binder ratios would be combined with three different solution modulus ratios, resulting in 6 different mix designs.

Each of the 6 mix designs would be tested at time intervals of 7 and 28 days, with 3 samples of each being manufactured. This would result in 6 samples for each mix design, and a total of 36 samples for experimental purposes.

Note that the initial project plan was based on casting significantly higher numbers of samples, however, the limited availability of concrete test cylinders and limited access to the engineering laboratory led to a significant scope reduction.

3.2 Materials

For the manufacture of the geopolymer concrete cylinders required for testing and experimental purposes, the following materials were used. These are discussed in more detail in the following sections:

1. Fly Ash;
2. Ground Granulated Blast Furnace Slag;
3. Sodium Hydroxide;
4. Sodium Silicate;
5. Fine Aggregates;
6. Coarse Aggregates.

3.2.1 Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS)

The selected fly ash was class F fly ash, obtained from Nielsen's Concrete Industries. It was identified as class F by its mineralogical / chemical compounds using the X-ray florescence technique. The table below shows the mass percentage of the different chemical compounds present in fly ash.

As already discussed, blast furnace slag (GGBFS) is a waste product from the steel industry, with the major constituent being Calcium Oxide (CaO). Geopolymer concretes prepared with only FA will take very long time to reach maximum strength, therefore adding GGBFS in the ratio 80 (FA) to 20 (GGBFS) or 70 (FA) to 30 (GGBFS) accelerates the curing process and setting time. The presence of CaO in GGBFS also enhances the compressive strength of the concrete. Again, the table below shows the chemical compounds present in GGBFS, in mass percentage, obtained through the X-ray florescence technique.

Chemical Compound	**Fly ash**	**GGBFS**	**Chemical Compound**	**Fly ash**	**GGBFS**
SiO_2(%)	55.83	33.68	CeO_2(%)	0.0264	-
Al_2O_3(%)	34.28	14.54	ZnO(%)	0.0129	-
CaO(%)	2.88	42.49	Nd_2O_3(%)	0.0116	-
MgO(%)	0.778	6.01	CuO(%)	0.0107	-
K_2O(%)	0.819	0.320	Y_2O_3(%)	0.0104	-

Na_2O(%)	0.269	0.180	S	-	1.07
Fe_2O_3(%)	2.43	0.551	Cl	-	0.0112
P_2O_5(%)	0.111	0.0215	LOI(%)	0.24	0.07
SO_3(%)	0.227	-	Total (%)	99.9555	99.9606
TiO_2(%)	1.77	0.616			
ZrO_2 (%)	0.0728	0.0351			
BaO(%)	0.0684	0.0536			
V_2O_5(%)	0.0427	-			
SrO(%)	0.0340	0.0722			
MnO(%)	0.0316	0.240			

Table 1.2.1 Chemical Composition of FA and GGBS

3.2.2 Sodium Hydroxide (NaOH)

Sodium hydroxide is used as one of the alkali activators. This chemical was obtained from Nielsen’s Concrete Industries, with a purity of 99%. NaOH increases the pH environment of the activator solution, which facilitates in breaking the strong alumina–silicate chains present in FA. This leads to the development of a three dimensional network of geopolymer chains.

3.2.3 Sodium Silicate (Na2SiO3)

Sodium silicate is used as one of the alkali activators. This chemical was obtained from Nielsen’s Concrete Industries, with the purity of 99%, and a modulus of 2.2 (ratio of SiO2 to Na2O). Apart from acting as a binder or alkali activator, sodium silicate also contributes towards the formation of the alumina-silicate chains of geopolymers.

3.2.4 Fine Aggregates (FAgg)

Fine aggregates (manufactured sand) were obtained from Nielsen’s Concrete Industries. The addition of sand ensures a homogeneous mix, filling the voids created by coarse aggregates. The table below describes the properties of the sand used as fine aggregate in the research project.

Description	**Manufactured Sand (fine Aggregate)**		**42917**
Test method	**Description**	**Test result**	**Exposure classification**
AS1141.4	uncompacted Bulk Density	1.69	-
	compacted bulk density	1.74	-
AS1141.6	Particle Density t/m^3 (DRY)	2.68	-
	Particle Density t/m^3 (SSD)	2.75	2.1-3.2 t/m^3
	Absorption (%)	2.6	-
AS 1141.11.1	Aggregate size (mm)		
	6.7mm	0	100
	4.75mm	100	90-100
	2.36mm	80	60-100
	1.18mm	55	30-100
	0.6mm	39	15-100
	0.425mm	34	-
	0.3mm	29	5-40
	0.15mm	22	0-25
	0.075 mm	17	0-20
AS 1141.12	Finer than 75 micron (%)	17	≤20%
AS 114.13	Finer than 2 microns (%)	1.6	1%
AS 1141.24	Sodium Sulphate Soundness (% Loss)	2.2	≤ 9%
AS 1141.31	Light Particals	nil	0.01
AS 1141.34	Organic impurities (other than sugar)	Pass	Lighter than referenced
AS 1141.35	Sugar	not detected	negative
AS1012.20	Chloride - acid Soluable Ci	0.01	≤0.01%
	Sulphate - Acid Soluable SO3^2	0.056	≤0.01%
AS 1289.3.7.1	SAND EQUIVELENT	70	60%
RMS T363	Accelerated Motar Bar Test for AAR Assesmenrt	0.01	≤0.1
1ssa No 145	Methane Blue Absorption Value	0.98	-

Table 3.2.2; Properties of Fine Aggregate Sand

3.2.5 Coarse Aggregate (CAgg)

Coarse aggregates were supplied by Nielsen’s Concrete Industries. CAgg is an important material in concrete as it takes the maximum proportion of load. The table below describes the properties of the course aggegate used in the research project.

Description	**10mm Concrete Aggregate**		**Jul-17**
Test method	**Description**	**Test result**	**Exposure classification**
AS1141.4	uncompacted Bulk Density	1.57	-
	compacted bulk density	1.64	-
AS1141.6	Particle Density t/m^3 (DRY)	2.79	-
	Particle Density t/m^3 (SSD)	2.81	2.1-3.2 t/m^3
	Absorption (%)	1.2	-
AS 1141.11.1	Aggregate size (mm)		
	26.5 mm	0	100
	19 mm	0	100
	13.2 mm	100	100
	9.5 mm	93	85-100
	6.7 mm	67	-
	4.75 mm	19	0-20
	2.36mm	3	0-5
	1.18 mm	2	-
	0.075 mm	2	0-2
AS 1141.12	Finer than 75 micron	2	0-2
AS 114.14	Misshapen Particles (3:1)	1	0-2
AS 1141.15	Flakiness index	12	≤10%
AS 1141.21	Aggregate crush Value (%)	8.7	-
AS 1141.22	10% fines (DRY)	340	-
	10%fines (wet)	250	min 80kN
	WET/DRY variations	26	35%
AS 1141.23	Los Angeles Abrasion Value (%)	13	-
AS 1141.24	Sodium Sulphate Soundness (% Loss)	2.2	≤ 9%
AS 1141.25	Degradation Factor (%)	81	50
AS 1141.31	Light Particles	nil	1%
AS 1141.32	Weak Particles	0.4	0.5% max
AS 1141.34	Organic impurities (other than sugar)	Pass	-
AS 1141.35	Sugar	not detected	negative
AS1012.20	Chloride - acid Soluble	0.018	
	Sulphate - Acid Soluble	0.08	
AS 1141.40	polished Aggregate Friction Value	45	

Table 23.2.3.Properties of Course Aggregate

3.3 Water

Normal tap water was used in the production of the geopolymer concrete test cylinders.

3.4 Preparation of Alkaline Activator

The original modulus of sodium silicate (SiO_2/Na_2O) is 2.2. The intention was to vary this modulus by adding NaOH. By calculating the mass percentage contribution Na_2O by sodium silicate and sodium hydroxide, three sets of alkaline solution with modulus of 1.2, 1.5 and 1.8 were developed.

The sodium hydroxide and sodium silicate were both dissolved in warm water. The resulting activator solutions were stored for a day to stabilize the dissolution. It is usually advisable to use the activator solution within three days. Further details are provided in the following section.

3.5 Calculation for Modulus of Alkali Activator

A 30kg mix design with an activator modulus range of 1.2, 1.5, and 1.8. were used, in conjunction with1 part binder to 2 parts fine aggregate to 4 parts coarse aggregate. As the method of calculating the modulus is complex a detailed explanation of the calculations is given. Note that the data provided in the table below provides the base information used in the calculations.

Chemical	Atomic weight	Number of atoms	Total atomic weight
Na	22.98977	2	45.978
Si	28.0855	1	28.0855
0	15.9774	3	47.9982
Weight			121.16332
SiO	60.0843		

Table 3.5.1; Base Information, (chemical Break-down of Elements)

3.5.1 Determination the weight of water

For a 70% water to 30% activator dilution, it is required to break the chemicals down into their parts as follows:

$$[Na_2SiO_3 \text{ (sodium Silicate)} + NaOH \text{ (Sodium Hydroxide)}] + [H_2O \text{ (water)}] = 2.421kg$$

$$H_2O \text{ (water)} = 2.421*0.7= \quad 1.6927 \text{ kg}$$

$$Na_2SiO_3 + NaOH = 2.421-19927 = 0.7263 \text{ kg}$$

For an 80% water to 20% activator dilution, it is required to break the chemicals down into their parts as follows:

Na_2SiO_3 (sodium Silicate) + NaOH (Sodium Hydroxide) + H_2O (water) = 2.421kg
Weight of H_2O (water) =2.421*087= 1.9368 kg
Na_2SiO_3+NaOH = 2.421-19927 = 0.7263 kg

For a target modulus of 1.2, it is a requirement to add to the sodium silicate (to lower the modulus). This poses a problem as the original modulus of Na_2SiO_3 has a modulus of 2.2 when dissolved in water.

$$\frac{\boldsymbol{SiO_2}}{\boldsymbol{Na_2 0}} = \mathbf{2.2}$$

To change the modulus, it is necessary to alter the amount of Na20. This is achieved by adding 40g of Na2 O Si O3 to arrive at 31g of Na2O. The original modulus of $Na_2Si\ O_3$ is typically 2-2.2, and the $Na_2Si\ O_3$ we are using has a modulus of 2.2. Therefore:

$$\mathbf{1.2}\ \boldsymbol{modulus} = \frac{\mathbf{2.2}}{\mathbf{1}+\boldsymbol{X}} = \mathbf{1.2}\ \equiv \mathbf{1}+\boldsymbol{x} = \frac{\mathbf{2.2}}{\mathbf{1.2}} \equiv \boldsymbol{X} = \frac{\mathbf{2.2}}{\mathbf{1.2}} - \mathbf{1} \equiv \boldsymbol{X} = \mathbf{0.8333}\%$$

$$\mathbf{1.5}\ \boldsymbol{modulus} = \frac{\mathbf{2.2}}{\mathbf{1}+\boldsymbol{X}} = \mathbf{1.5}\ \equiv \mathbf{1}+\boldsymbol{x} = \frac{\mathbf{2.2}}{\mathbf{1.5}} \equiv \boldsymbol{X} = \frac{\mathbf{2.2}}{\mathbf{1.5}} - \mathbf{1} \equiv \boldsymbol{X} = \mathbf{0.46667}\%$$

$$\mathbf{1.8}\ \boldsymbol{modulus} = \frac{\mathbf{2.2}}{\mathbf{1}+\boldsymbol{X}} = \mathbf{1.8}\ \equiv \mathbf{1}+\boldsymbol{x} = \frac{\mathbf{2.2}}{\mathbf{1.8}} \equiv \boldsymbol{X} = \frac{\mathbf{2.2}}{\mathbf{1.8}} - \mathbf{1} \equiv \boldsymbol{X} = \mathbf{0.2222}\%$$

3.5.2 Determine the amount of NaOH needed

40g of $Na_2O\ SiO_3$ gives 31g of Na_2O when dissolved in water.

$$\mathbf{1.2}\ \boldsymbol{modulus} = \frac{\mathbf{0.8333}}{\mathbf{2}} * \mathbf{40} = \mathbf{16.66}\boldsymbol{g\ of\ NaOH}$$

$$\mathbf{1.5}\ \boldsymbol{modulus} = \frac{\mathbf{0.46667}}{\mathbf{2}} * \mathbf{40} = \mathbf{9.333}\boldsymbol{g\ of\ NaOH}$$

$$\mathbf{1.8}\ \boldsymbol{modulus} = \frac{\mathbf{0.2222}}{\mathbf{2}} * \mathbf{40} = \mathbf{4.444}\boldsymbol{g\ of\ NaOH}$$

There for to determine the amount of sodium silicate that must be dissolved in water it is necessary to perform the following calculations:

1.2 Modulus

$$\mathbf{726.3} * \frac{\mathbf{182}}{\mathbf{198.44}} = \mathbf{666.13}\boldsymbol{g\ of\ Na_2SiO_3}$$

$$\mathbf{726.3} * \frac{\mathbf{16.66}}{\mathbf{198.44}} = \mathbf{60.98}\boldsymbol{g\ of\ NaOH}$$

1.5 Modulus

$$726.3 * \frac{182}{191.33} = 690.88g\ of\ Na_2SiO_3$$

$$726.3 * \frac{9.333}{191.33.} = 35.43g\ of\ NaOH$$

1.8 Modulus

$$726.3 * \frac{182}{186.44} = 706.99g\ of\ Na_2SiO_3$$

$$726.3 * \frac{4.44}{186.44} = 17.296g\ of\ NaOH$$

3.6 Mix Design

As already mentioned, the nominal mix ratio of 1:2:4 with a target compressive strength of 30MPa was adopted for the research work. The mix ratio was further subdivided in to several parts for the calculation of the individual mass of the materials. For the calculation of mass of materials, FA + GGBFS + sodium silicate + sodium hydroxide+ water was considered as one part in 1:2:4 mix ratio, with two parts of sand and 4 parts of coarse aggregate. The table below shows the mass proportions of different materials for 6 concrete cylinders.

80% Fly Ash:20% Blast Furnace Slag							
Modulus	Na_2SiO_3	$NaOH$	**Water**	**Fly ash**	**Slag**	**CAgg**	**FAgg**
	Sodium Silicate	**Sodium Hydroxide**	**Kg**	**Kg**	**Kg**	**Kg**	**Kg**
1.2	666.13	60.98.	1.6927	3.2688	0.8172	15.06	8.619
1.5	690.88	35.43					
1.8	706.99	17.296					
70% Fly Ash: 30% Blast Furnace Slag							
Modulus	Na_2SiO_3	$NaOH$	**Water**	**Fly ash**	**Slag**	**CAgg**	**FAgg**
	Sodium Silicate	**Sodium Hydroxide**	**Kg**	**Kg**	**Kg**	**Kg**	**Kg**
1.2	666.13	60.98.	1.6927	2.86	1.22	15.06	8.619
1.5	690.88	35.43					
1.8	706.99	17.296					

Table 3.2.5; Geopolymer Mix Design for 6 Sample Cylinders (30kg)

3.7 Mixing, Workability, Curing, and Testing the Geopolymer Mixes

3.7.2 Mixing

All the materials used for the mixed design were weighed accurately and mixed thoroughly using a drum mixer with 45 litre capacity. The procedure for mixing was as follows:

1. Turn on the mixer and add alkali activator solution;
2. Add FA and GGBFs to mixer;
3. Wait for 20 to 30 seconds to allow formation of a smooth homogeneous binder mix;
4. Add sand to the mixer and mix thoroughly for 0.5 to 1 minute;
5. Add coarse aggregate and allow all the ingredients to form a homogeneous mixture;
6. Once a homogeneous mixture is achieved, pour the concrete into a trolley;
7. Using the trolleyed mix, fill the slump cone in 3 layers with 25 tamping for each layer;
8. Using the trolleyed mix, filled the cylindrical mould (dimension 200mm height x 100mm diameter). Note it was important to maintain the density of 2400kg/m3 of fresh concrete. Therefore the concrete was poured into each cylindrical mould in three successive layers with 25 tamping for every layer;
9. Once the cylinder was completely filled, smooth the top surface using a trowel.

3.7.2 Workability (Slump Test)

The slump test is performed to determine the workability of the mix (i.e. how easily the concrete flows). The aim is to ensure uniformity between different batches of concrete under field conditions. The metal mould, known as the slump cone or Abrams cone, is open at both ends and has handles attached on both sides to allow it to be removed vertically. This minimises the disturbance of the sample. The cone is placed on a ridged dampened non-porous surface and is filled in three layers. The concrete sample layers are rodded 25 times with a 10mm diameter steel rod with a hemispherical tip and be between 450-600mm in length. The concrete is struck flush with the top of the mould after last rodding. The mould is then lifted vertically with care, to ensure the concrete sample is not disturbed. The concrete then slumps under its own weight, and the height between the top of the mould and the top of the concrete is measured within 2 minutes of sampling. This distance is referred to as the slump of the concrete sample. Details of all parts of the procedure are shown in the figure below.

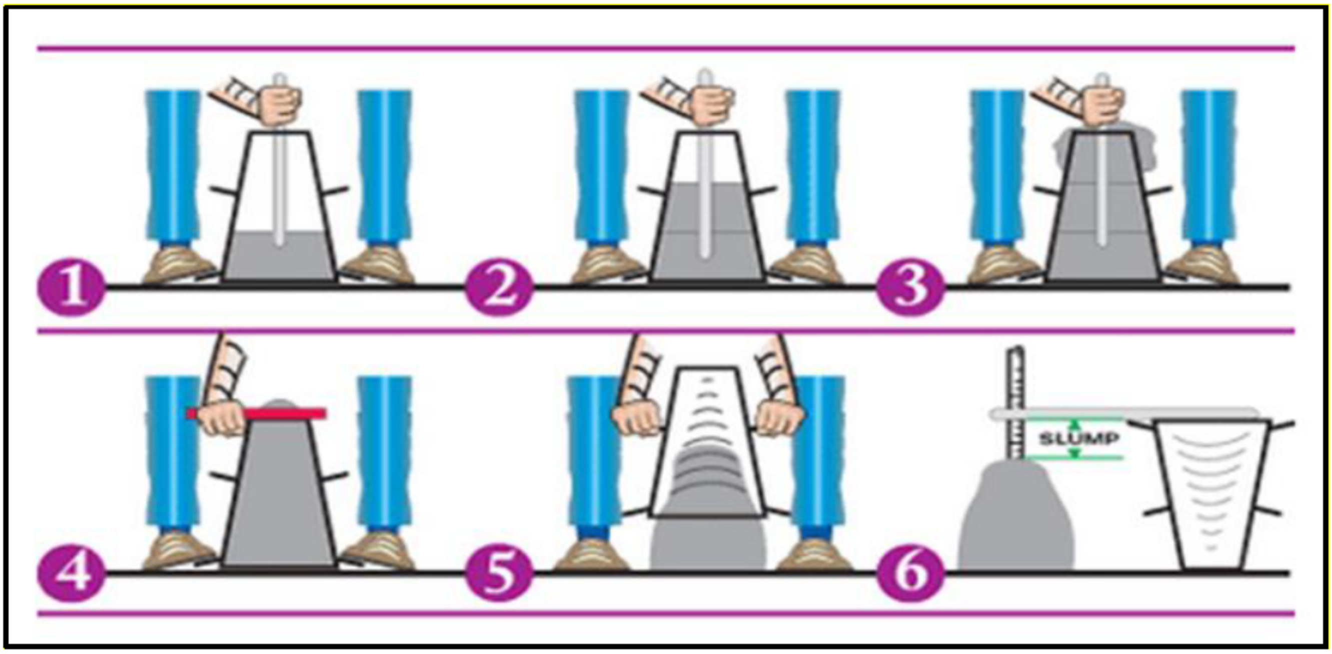


Figure 3.7.5; Slump Test Procedures

The slump of the concrete can take on 3 different profiles as follows. Refer also to the diagrams below which illustrates all 3 cases, and include an example of a typical slump results achieved in the research work. All slump tests were carried out in accordance with AS 1012.3.1.

<u>Collapse</u>

This usually indicates that the sample is to wet or has a high workability, and not suitable for a slump test.

<u>Shear</u>

This usually indicates one of three possibilities; the sample was disturbed by the mould during removal; the mix is to dry (this could also give a zero slump); the mould was not properly cleaned and oiled before the sample was tested.

<u>True Slump</u>

This is how a slump sample should look and is indicative of an accurate reading.

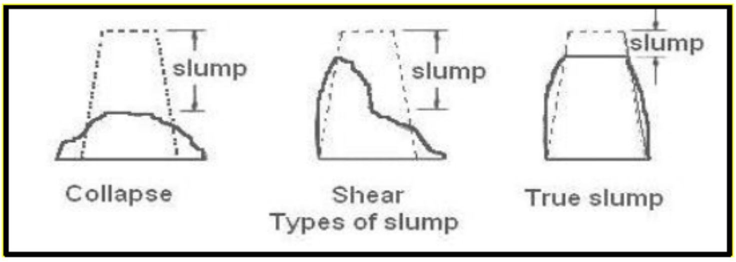


Figure 3.7.6; Slump Profiles

Figure 3.7.7; Typical Project Slump Profile

The desired slump range for the research project was determined. For adequate workability, this was 250-300mm. This may seem high in relation to OPC concrete slump tests, (80mm-100mm), however, due to the fact that geopolymer concrete cannot be vibrated and compacted, and has a very quick setting time, high followability is necessary to ensure there are no unwanted voids.

3.7.3 Curing

The concrete samples were allowed to set for 24 hours. They were then carefully removed from their moulds, and were then wrapped using plastic. They were also adequately labelled.

These samples were kept inside the lab at a temperature range of 23°C – 25°C. They remained in an undisturbed state until they were taken for the compression strength measurements. This occurred after 7 days and 28 days of curing.

3.7.4 Testing

After removing the samples from the curing condition, all uneven surfaces were smoothened prior to testing. The samples were then compression tested (after 7 and 28 days). They were tested in compression testing machine. The test method was a displacement controlled compression test.

3.7.5 Data Acquisition

Force and displacement were acquired from compression testing machine. This allowed determination of the compressive strength, the strain-strain relationship, and the elastic modulus.

4. RESULTS INTERPRETATION AND DISCUSSION

4.1 Summary of Results

4.1.1 Table of compression test results

Mix			Casting			testing					
Fly-Ash/blast furnace slag ratio	binder modulus	sample number	Casting date	SLUMP (max slump 300mm)	observations	7 day testing date	Max Compression Load(kN)		28 day testing date	Max Compression load (kN)	remarks
80:20	1.2	1	12/8/17	300	mix went in very wet and leaked out of bottom of slump cone	22/09/2017	60.18	looked like bonding failure	10/10/2017	115.1819458	looked like bonding failure could see signs where mortar pulled away from Course aggragate. Closer to compression failure (no Cracks)
		2		300			62.69			100.6394577	
		3		300			53.54			94.23693848	
	1.5	1	12/09/2017	300	mix went in very wet and leaked out of bottom of slump cone. Rapid setting	22/09/2017	109.02	looked like bonding failure could see signs where mortar pulled away from Course aggragate.	10/10/2017	156.655304	Had compresion failure started to get a cone shape to the cylinder. Still some bonding failure but with aggragate failure
		2		300			110.11			171.7317352	
		3		300			109.59			138.3435974	
	1.8	1	28/08/2017	300	mix went in very wet and leaked out of bottom of slump cone. Rapid setting	5/09/2017	43.14	looked like bonding failure	3/10/2017	132.02	looked like bonding failure could see signs where mortar pulled away from Course aggragate
		2		300			47.88			106.87	
		3		300			55.58			153.72	
70 : 30	1.2	1	5/09/2017	300	mix went in very wet and leaked out of bottom of slump cone. Very Rapid setting almost unworkable by last casting	12/09/2017	102.25	looked like bonding failure could see signs where mortar pulled away from Course aggragate	5/10/2017	76.73	looked like mainly bonding failure could see signs where mortar pulled away from Course aggragate. Some signs of aggragtae failure
		2		300			107.19			160.91	
		3		300			118.16			235.76	
	1.5	1	5/09/2017	300	mix went in very wet and leaked out of bottom of slump cone. Very Rapid setting almost unworkable by last casting	12/09/2017	106.14	looked like bonding failure could see signs where mortar pulled away from Course aggragate	5/010/2017	219.09	looked like mainly bonding failure could see signs where mortar pulled away from Course aggragate. Some signs of aggragtae failure
		2		300			111.05			190.09	
		3		300			109.13			235.72	
	1.8	1	28/08/2017	300	mix went in very wet and leaked out of bottom of slump cone. Very Rapid setting almost unworkable by last casting	5/09/2017	169.33	looked like bonding failure could see signs where mortar pulled away from Course aggragate	3/10/2017	148.29	looked like mixture of bonding and aggragate failure, could see signs where mortar pulled away from Course aggragate. signs of aggragtae failure
		2		300			186.19			311.68	
		3		300			171.51			155.13	

Table4.1; record of Casting and testing with visual observations

4.2 Discussion of results

4.2.1 70:30 Compression tests

Due to the fast setting time of geopolymer cement, getting a smooth surface to the top of test samples can be problematic. The uneven compression surface necessitated the use of a sample cap, to provide a smooth and level surface for the piston to act against.

The compression testing machine used for this project has an external memory unit that did not allow for the zeroing of the test once the free play between the piston and the cap was taken up. Looking at the Compression load Graph below this period has been left in, (for the first Graph only), to illustrate the amount of distance the piston had to move before making solid contact.

In some cases, due to the compression surface, this travel extended well after the piston made initial contact with the sample and a settling or surface crushing took place. In later graphs, this displacement has been accounted for and removed from the calculations.

4.2.1.1 7 Days Load Test

70:30:1.2

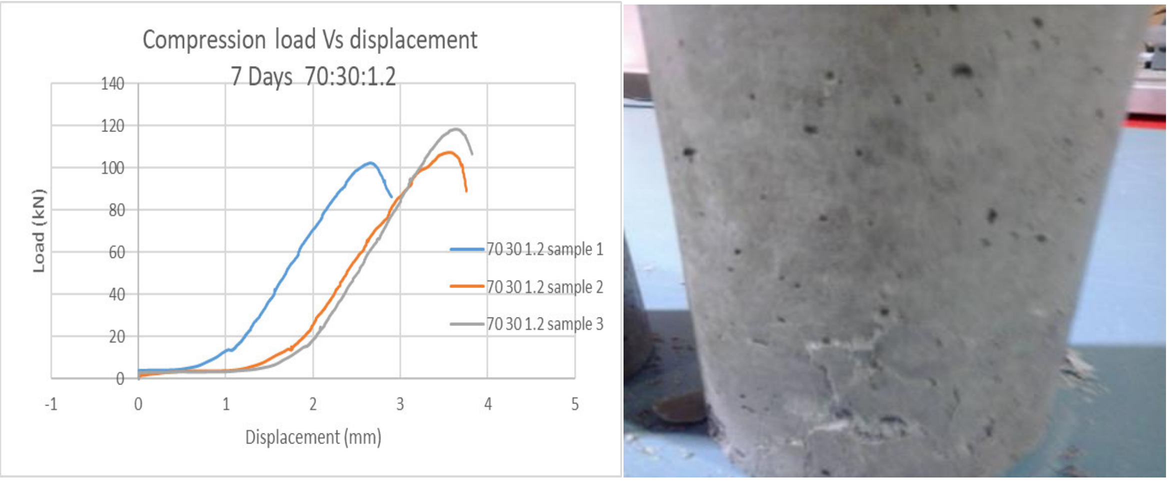


Figure 4.2.1; 70:30:1.2 7DAY compression test with sample photo

Maximum Load
sample 1; 102.2494583 kN
sample 2; 107.1892242 kN
sample 3; 118.1566849 kN

The Data from the graph for the seven-day compression load placed on the samples for a 70%FA:30%GBFS with an activator modulus of 1.2, (Figure 20 above), after the initial settling of the piston, there is a smooth almost linear track to the compression slope. The Final Maximum load that each sample received ranged between 100-120kN, this indicates that all of the samples are superficially uniform and should give similar uniform results. From the graph it can see that all the test samples had a crush displacement of approximately 1 ½ millimetres, this indicates that while at this stage of curing the mix design is not read for being constructed upon as it is soft and cannot be considered suitable for placement under load,

70:30:1.5

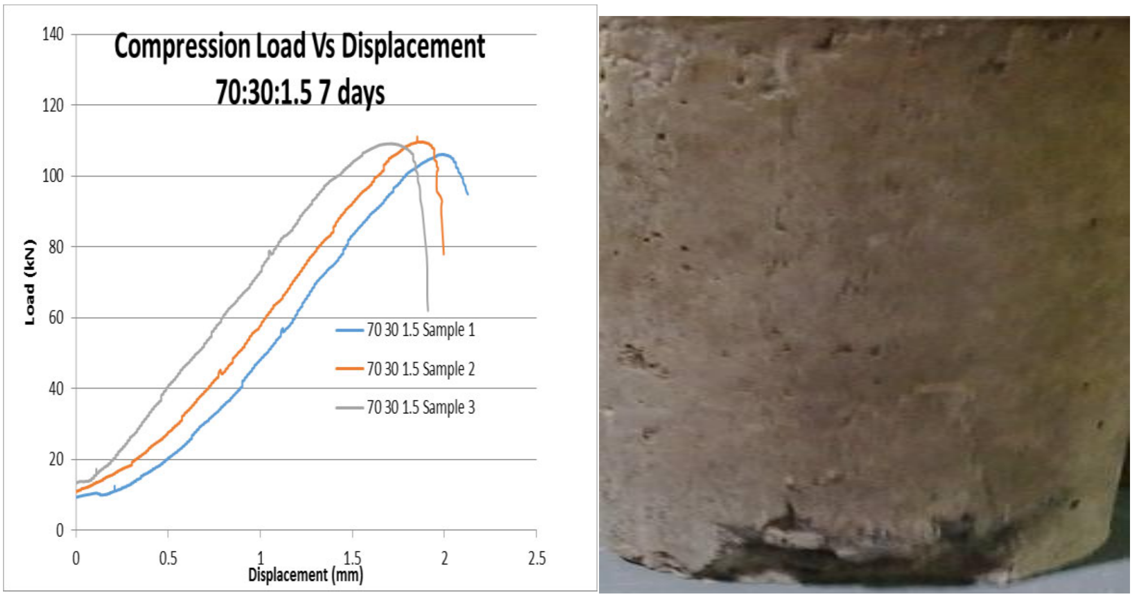


Figure 4.2.2; 70:30:1.5 7 DAY compression Test with sample Photograph

Max Load
sample 1;   106.1379013 kN
sample 2;   111.0474091 kN
sample 3; 109.1306915 kN

The Data from the graph for the seven-day compression load placed on the samples for a 70%FA:30%GBFS with an activator modulus of 1.5, (Figure 21 above), show that the smooth almost linear track to the compression slope that should be expected is missing in the results. Small jumps in the data can be seen. The Final Maximum load that each sample received ranged between 105-110kN, almost the same as the results for the previous modulus. These two data points could indicate that there are micro voids in the all of the samples, and this has caused small collapses while under load and allowed for a weakness in the samples.

While all the samples are still superficially uniform and similar uniform results should be expected for 28 days. From the graph it can see that all the test samples had a crush displacement of approximately 1 ¾ millimeters, this indicates that while at this stage of curing the mix design is not read for being constructed upon as it is soft and cannot be considered suitable for placement under load,

70:30:1.8

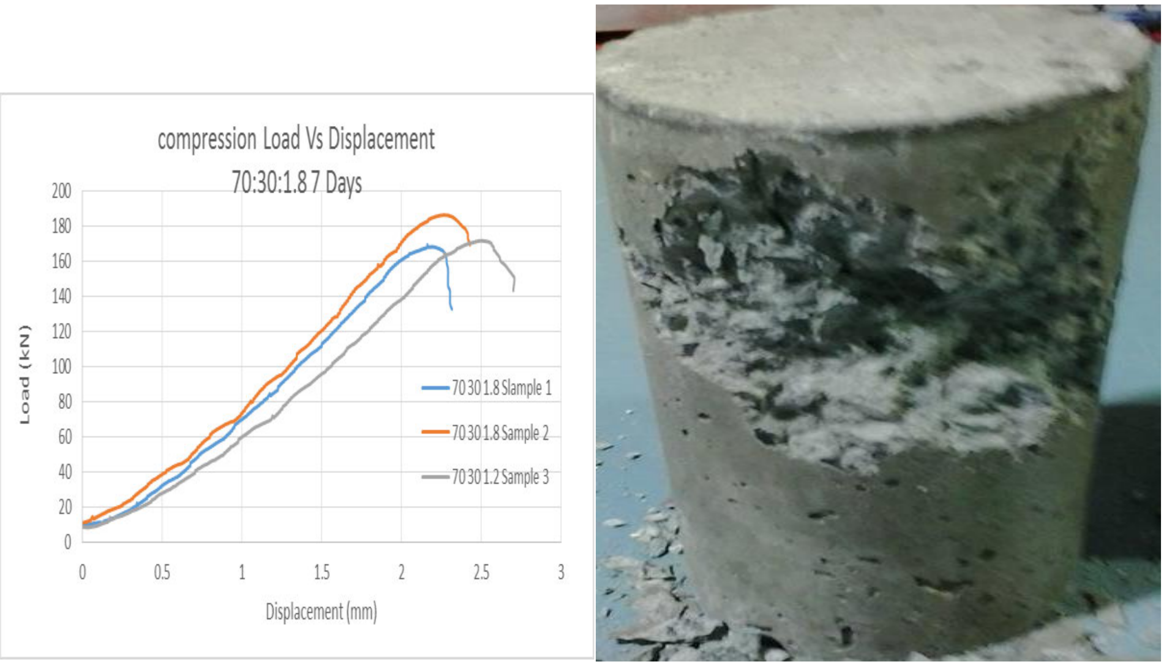


Figure4.2.3; 70 30 1.8 7 DAY compression results with sample Photo

Maximum Load
sample 1; 169.3322296 kN
sample 2; 186.1859283 kN
sample 3; 171.5124359 kN

The Data from the graph for the seven-day compression load placed on the samples for a 70%FA:30%GBFS with an activator modulus of 1.8, (Figure 22 above), While there is a linear track to the compression slope it is rough indicating micro voids. The Final Maximum load that each sample received ranged approximately between 170-185kN, and all follow a similar plot. This indicates that all of the samples are superficially uniform and should give similar uniform results. From the graph, it can see that all the test samples had a crush displacement of approximately 2 ¼ millimeters, this indicates that while at this stage of curing the mix design is not read for being constructed upon as it is soft and cannot be considered suitable for placement under load,

6.2.1.2 28 Days

70:30:1.2

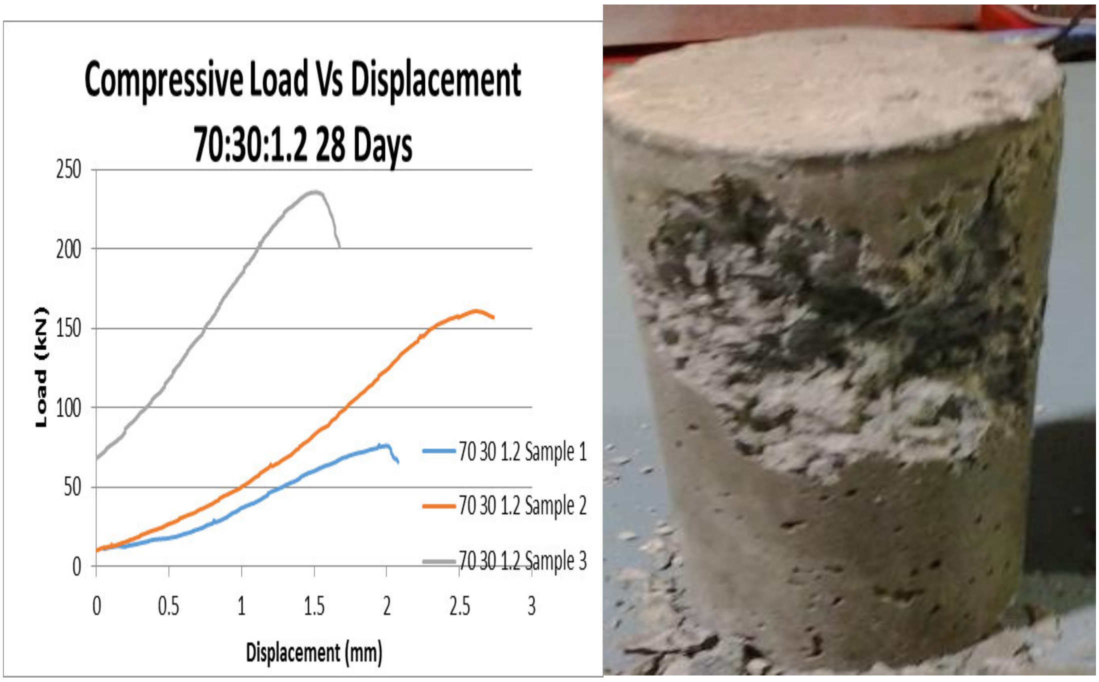


Figure 4.2.4; 70:30:1.2 28 DAY compression results with Photo

Maximum Load
sample 1; 76.73373413 kN
sample 2; 160.9128418 kN
sample 3; 235.7550812 kN

The Data from the graph for the twenty-eight-day compression load placed on the samples for a 70%FA:30%GBFS with an activator modulus of 1.2, (Figure 23 above), illustrate that there is a discrepancy in the data.

- Sample 1 is week only holding 76kN before failing and has a large displacement this could be indicative of there is a weakness to the sample and that the data is unreliable.
- Sample 2 held a larger load but also had a large displacement. This could indicate that a geopolymer cement with this mix design has a large crush dimension, and should be closely compared to the 28 day results.
- Sample 3 has a high load capacity holding almost 50% more than sample 2. While unusually hard sample is possible this could be an indicator of this samples true strength. No concrete conclusion can be made at this point

While the data differs dramatically there is a smooth track to the compression slope indicating that there are no voids in the samples.

70:30:1.5

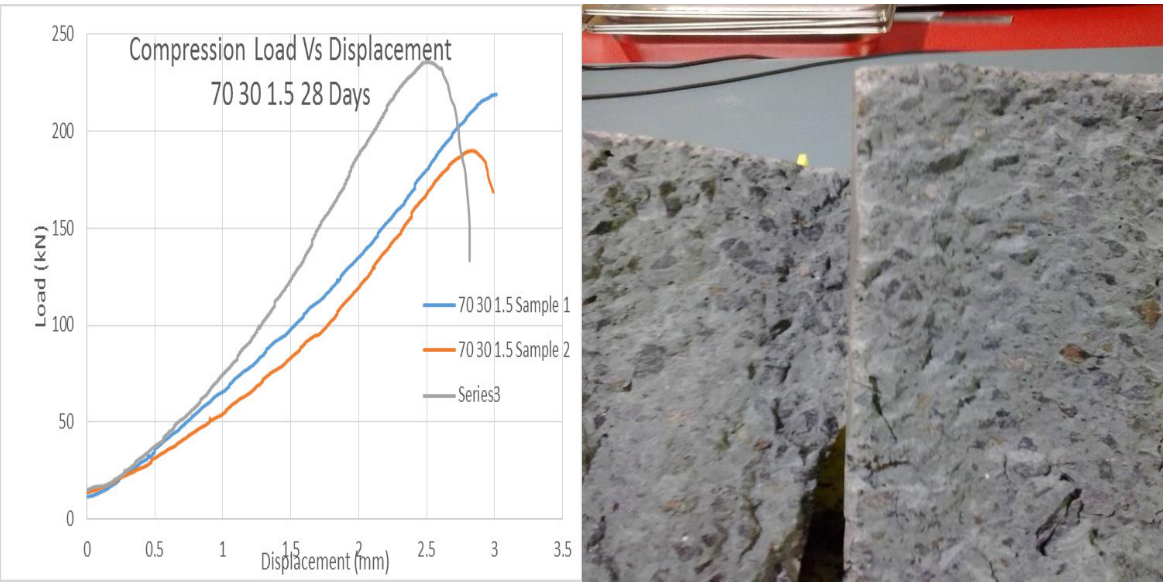


Figure 4.2.5; 70 30 1.8 28 DAY compression results with Photo

Maximum Load
sample 1;   219.0879364 kN
sample 2;   190.0917358 kN
sample 3; 190.0917358 kN

The Data from the graph for the twenty-eight-day compression load placed on the samples for a 70%FA:30%GBFS with an activator modulus of 1.5, (Figure 24 above), The linear track to the compression slope it evident and follows a smooth path, indicating limited voids in the test samples. While one sample, (sample 3) deviates from the other two samples 1 and 2 follow an almost identical part suggesting that they are accurate results. Both reach a load capacity of 190kN but have a displacement of 2 ½ millimetres indicating that this mix has a large elastic modulus.

70:30:1.8

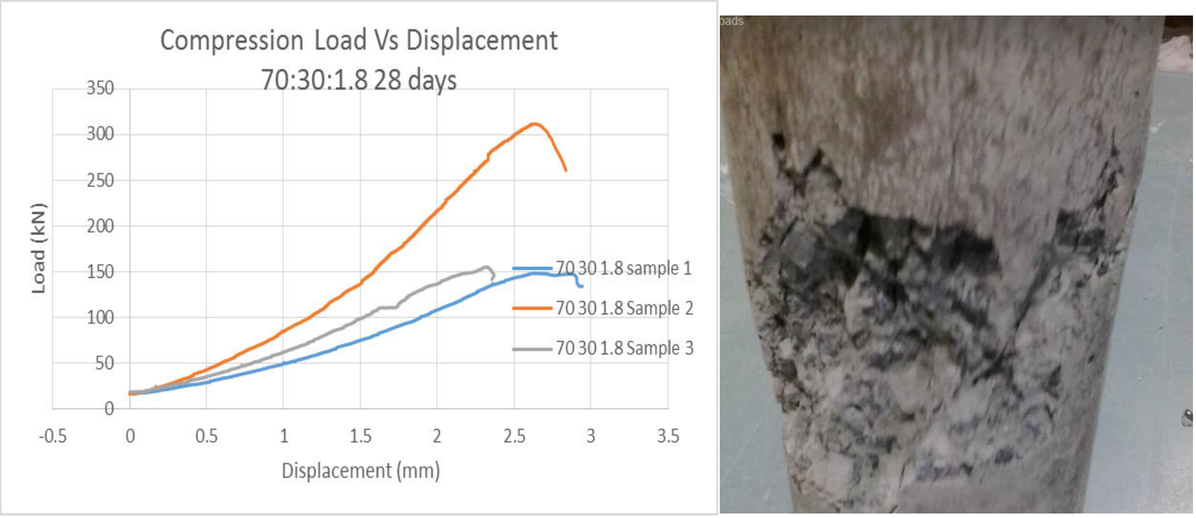


Figure 4.2.6; 70:30:1.8 28DAY compression results with Photo

Maximum Load
sample 1;   148.29237kN
sample 2;   311.6814575kN
sample 3; 155.1269073kN

The Data from the graph for the seven-day compression load placed on the samples for a 70%FA:30%GBFS with an activator modulus of 1.8, (Figure 25 above), the photo shows the 311kN sample failed in a what indicated a compression failure.

The data from this test gives two different possibilities.

- Samples 2 and 3 only have a load capacity of 150kN less that the 7 day results. This could indicate that the binder is failing and the cement is becoming weaker at time progresses. Sample 3 at approximately 110kN has a small plateau indicating a localised failure before continuing.
- Sample 1 has a load capacity of 310k, using the same logic as with Portland cement, the strength of the concrete should be expected to be higher at 28 days. Following this train of thought, a load capacity of 310kN is a reasonable expectation for 28 days.

4.2.2 80:20 Compression results

4.2.2.1 7 days

80:20:1.2

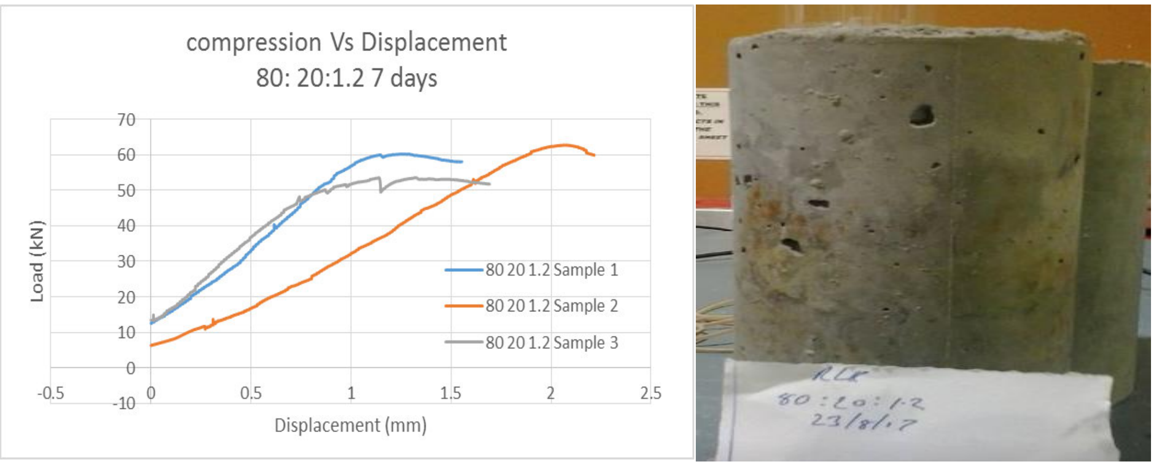


Figure 4.2.7; 80:20:1.2 7 DAY compression results

Maximum Load
sample 1; 60.181 kN
sample 2; 62.694458kN
sample 3; 53.5444069kN

The Data from the graph for the seven-day compression load placed on the samples for an 80%FA:20%GBFS with an activator modulus of 1.2, (Figure 26 above), indicates a diverging data stream again. The Final Maximum loads all the samples remains around the 60kN mark but show a differing displacement. . as sample two has almost double the displacement of samples one and three it could be argued that it may contain micro voids allowing for aa more significant crush displacement

80:20:1.5

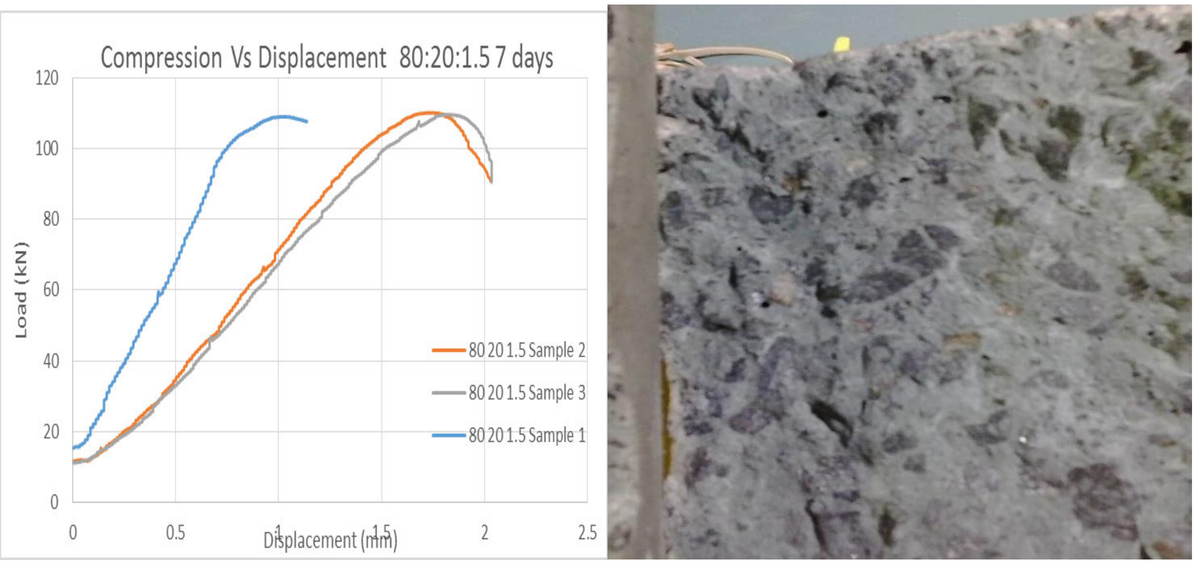


Figure 4.2.8; 80:20:1.5 7 DAY compression results

Max Load
sample 1; 109.024834 kN

sample 2; 110.10891 kN
sample 3; 109.59024 kN

The Data from the graph for the seven-day compression load placed on the samples for an 80%FA:20%GBFS with an activator modulus of 1.5, (Figure 27 above), Highlight that Samples two and three again are almost following the same path suggesting that they are the true results. While all samples show a load capacity of 100kN again, the displacement differs between the samples.

80:20:1.8

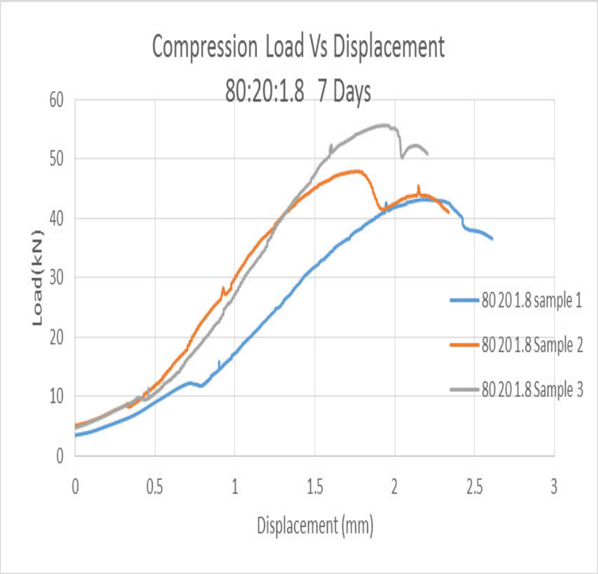


Figure4.2.9; 80:20:1.8 7 DAY compression results

Max Load
sample 1; 43.1446152 kN
sample 2; 47.8775902 kN
sample 3; 55.5814095 kN

The Data from the graph for the seven-day compression load placed on the samples for an 80%FA:20%GBFS with an activator modulus of 1.8, (Figure 28 above), illustrate that all the samples have suffered from localised failures indicating that there are voids and possible weakness in the samples.

6.2.2.2 28 Days

80:20:1.2

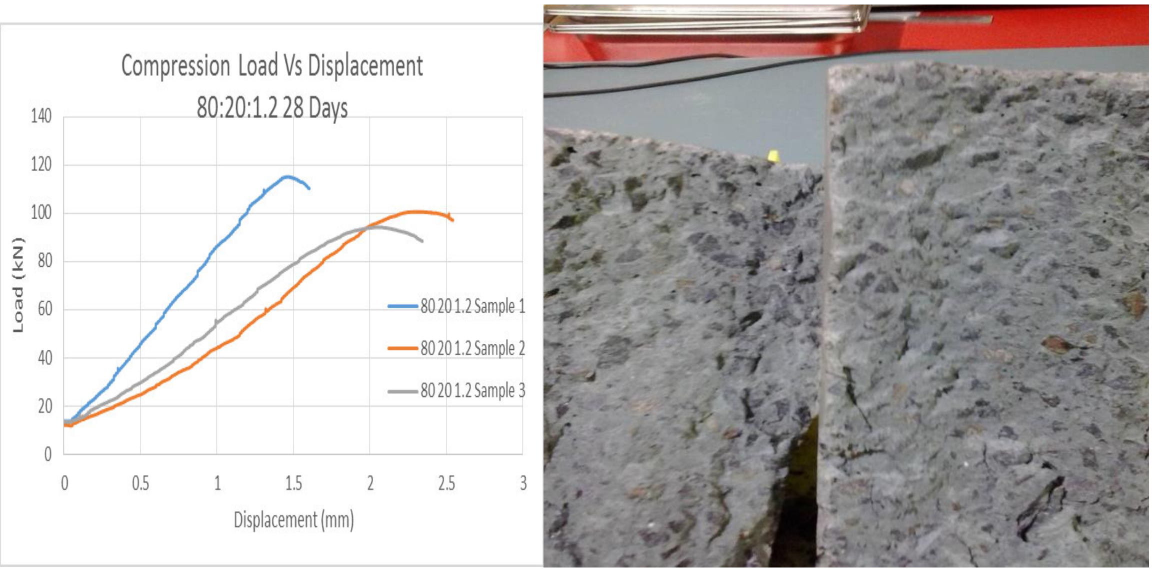


Figure 4.2.10; 80:20:1.2 28 DAY compression Results with sample photograph

Max Load

Sample 1 115.181945800781 kN
Sample 2 100.639457702636 KN
Sample 3 94.2369384765625 kN

The Data from the graph for the twenty-eight-day compression load placed on the samples for an 80%FA:20%GBFS with an activator modulus of 1.2, (Figure 29 above). Again, mico voids are indicated by the slight jaggedness of the compression load path this sample split along the centre indicating a bonding failure to the test sample it can be seen where the mortar has pulled away from the coarse aggregate.

Figure4.2.11; image of mark left after bond between mortar and aggregate fails

80:20:1.5

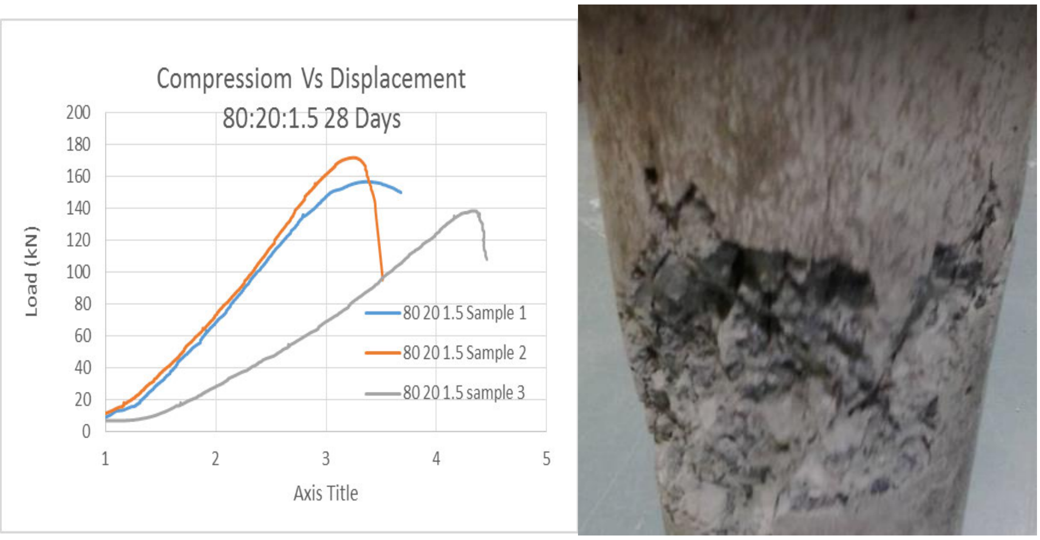


Figure 4.2.12; 80:20:1.5 28 DAY Compression Results

Max Load

Sample 1; 156.655303955078 kN

Sample 2; 171.731735229492 kN

Sample 3; 138.343597412109 kN

The Data from the graph for the seven-day compression load placed on the samples for a 80%FA:20%GBFS with an activator modulus of 1.5, (Figure 30 above). The Data suggested that sample 3 had a lot of micro-voids leading to a significant displacement.

80:20:1.8

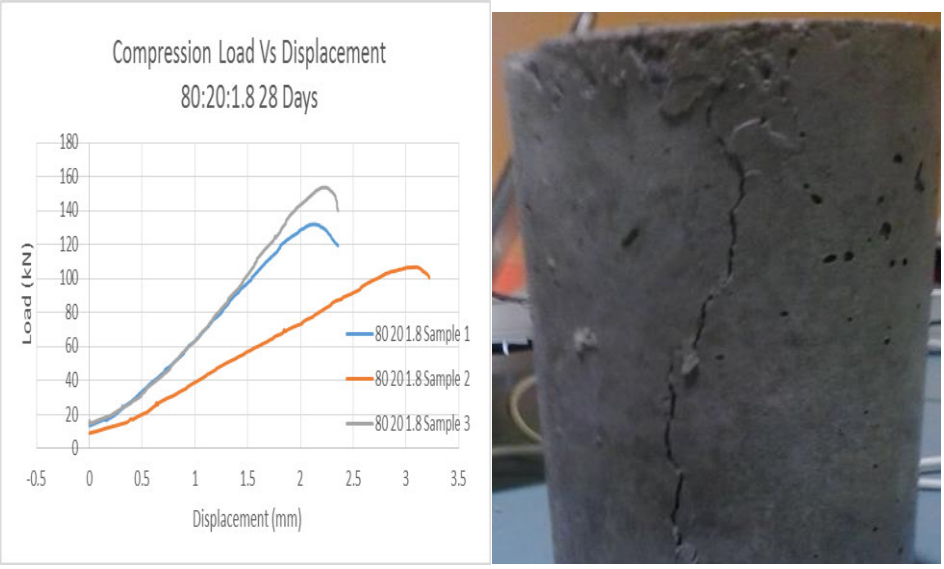


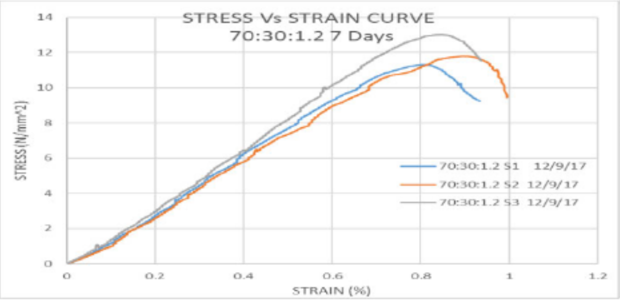
Figure4.2.13; 80:20:1.8 28 DAY compression results

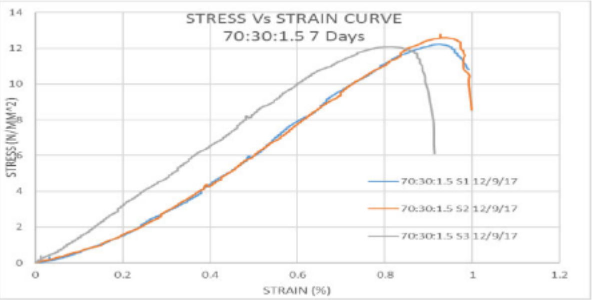
Max Load
sample 1; 132.01741kN
sample 2; 106.867882kN
sample 3; 153.72141kN

The Data from the graph for the twenty eight-day compression load placed on the samples for a 80%FA:20%GBFS with an activator modulus of 1.8, (Figure 31 above), the data for samples one and two follow almost identical paths and have a load capacity around 160kN's this would follow on logically from the results from the seven day results.

4.3 70:30 Compression Strength

7 days





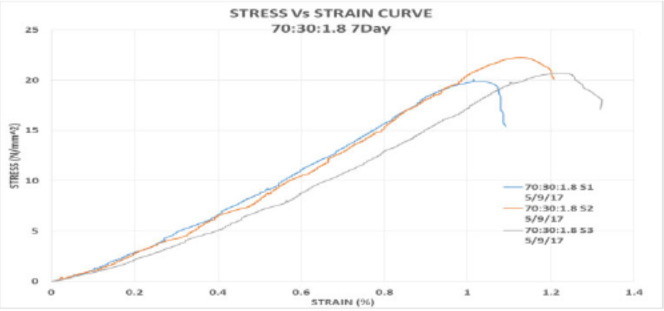


Figure 4.3.1; 70:30:1.2 7DAY Compression Strength

Figure 4.3.2; 70:30:1.5 7DAY Compression Strength

Figure 4.3.34; 70:30:1.8 7Day Compression Strength

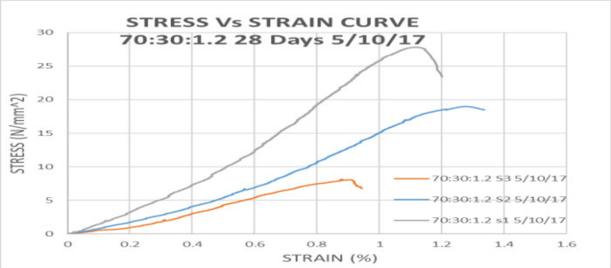
7 DAYS								
		STRAIN(%)				STRESS(N/mm^2)		
				AVERAGE				Average Mpa
70:30:1.2 12/9/17	S1	MAX	0.932725	0.95535686	S1	MAX	11.31535	12.03488
	S2	MAX	0.996082		S2	MAX	11.77971	
	S3	MAX	0.937263		S3	MAX	13.00959	
70:30:1.5 12/9/17	S1	MAX	0.991812	0.96791776	S1	MAX	12.24255	12.3684
	S2	MAX	0.998241		S2	MAX	12.76422	
	S3	MAX	0.9137		S3	MAX	12.09842	
70:30:1.8 5/9/17/	S1	MAX	1.091705	1.20752843	S1	MAX	20.06518	21.00503
	S2	MAX	1.207853		S2	MAX	22.24713	
	S3	MAX	1.323027		S3	MAX	20.70279	

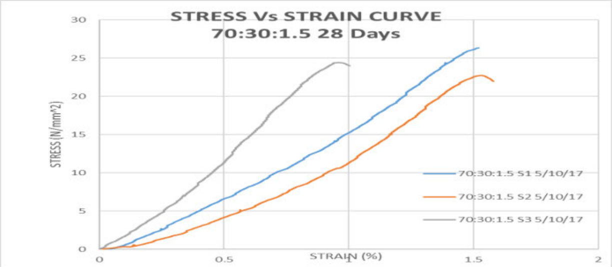
Table 4.3.1; table of 70:30:7 DAY stress and strain results

The stress-strain curves mirror the results found from the compression load results. 70:30:1.5 shows the same stagnation in the max stress as is found before; Logic dictates that a max shear around 16 MPA could reasonably be expected from the modulus if 1.5 as it is midway between 1.2 and 1.8. Without the possibility of doing a recasting of the (70:30:1.5), Design Mix to confirm the results achieved, one of two conclusions can be deduced at this time

1. The changing modulus from 1.2 to 1.5 has no noticeable effect on the compressive strength of the samples.
2. The design mix sample has not compacted correctly and as a result did not achieve the desired strength. As increasing the amount of GGBFS in the mix will speed up the setting time it is possible that this resulted in improper compaction.

28 days





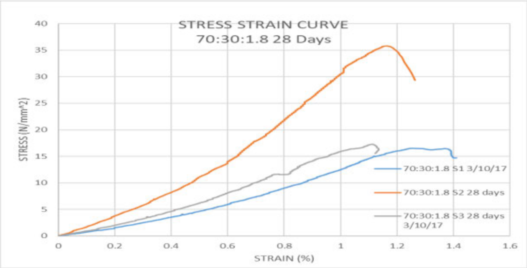
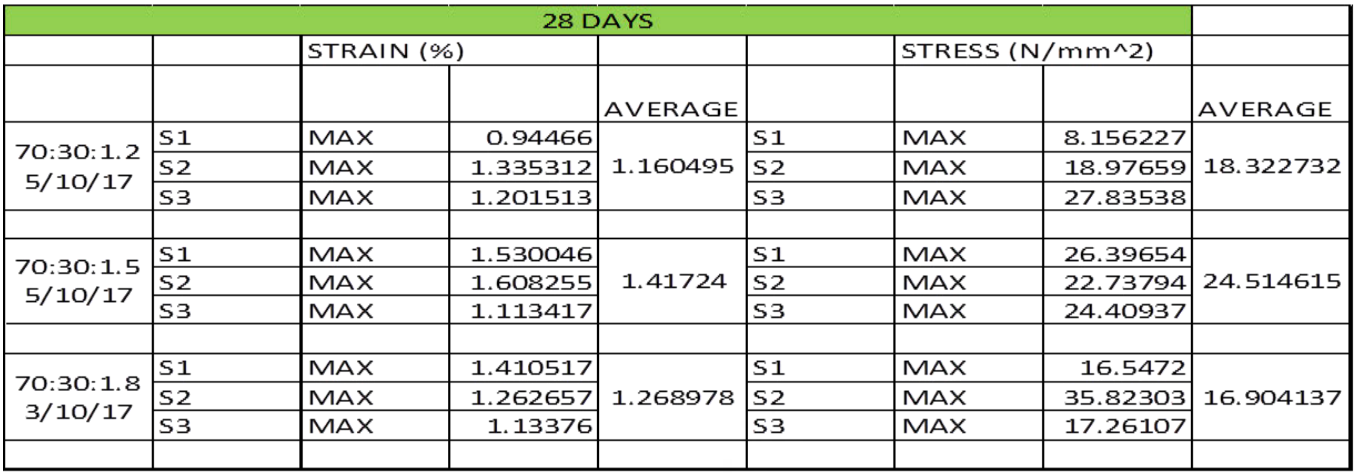


Figure4.3.4; 70:30:1.2 28 Day Compression Strength

Figure 4.3.5; 70:30:1.5 28Day Compression Strength

Figure 4.3.6; 70:30:1.8 28 Day compression Strength



28 DAYS									
		STRAIN (%)				STRESS (N/mm^2)			
				AVERAGE				AVERAGE	
70:30:1.2 5/10/17	S1	MAX	0.94466	1.160495	S1	MAX	8.156227	18.322732	
	S2	MAX	1.335312		S2	MAX	18.97659		
	S3	MAX	1.201513		S3	MAX	27.83538		
70:30:1.5 5/10/17	S1	MAX	1.530046	1.41724	S1	MAX	26.39654	24.514615	
	S2	MAX	1.608255		S2	MAX	22.73794		
	S3	MAX	1.113417		S3	MAX	24.40937		
70:30:1.8 3/10/17	S1	MAX	1.410517	1.268978	S1	MAX	16.5472	16.904137	
	S2	MAX	1.262657		S2	MAX	35.82303		
	S3	MAX	1.13376		S3	MAX	17.26107		

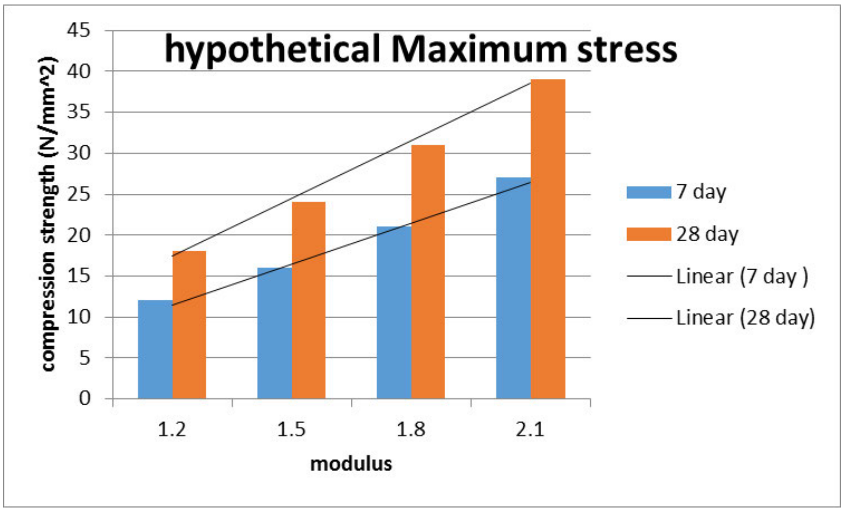
Table 4.3.1; 28 Day Stress Strain Results

When examining the results for the 28 Day compression strength, at first, they seem country to the logical results expected. When the two lower figures of the Max stress for 70:30:1.8 are removed from the table, the results look slightly different. The table below shows that the maximum shear average follows an almost predictable flow.

28 DAYS								
		STRAIN (%)				STRESS (N/mm^2)		
				AVERAGE				AVERAGE
70:30:1.2 5/10/17	S1	MAX	0.94466	1.160495	S1	MAX	8.156227	18.322732
	S2	MAX	1.335312		S2	MAX	18.97659	
	S3	MAX	1.201513		S3	MAX	27.83538	
70:30:1.5 5/10/17	S1	MAX	1.530046	1.41724	S1	MAX	26.39654	24.514615
	S2	MAX	1.608255		S2	MAX	22.73794	
	S3	MAX	1.113417		S3	MAX	24.40937	
70:30:1.8 3/10/17	S1	MAX	1.410517	1.268978	S1	MAX	16.5472	35.823032
	S2	MAX	1.262657		S2	MAX	35.82303	
	S3	MAX	1.13376		S3	MAX	17.26107	

Table 4.3.2; 28 Day Adjusted Stress Strain Results

If the same logic is followed with the seven day results new table comes into being. This gives a predictable progression to the compressive strength and a possible prediction of what results may be achieved. While these figures used in the tables below are unsubstantiated, they are a definite point of research that should be examined at a future date.



	7 day		28 day		
Modulus	results achieved	results expected	results achieved	results expected	spread
1.2	12	12	18	18	6
1.5	12	16	24	24	8
1.8	21	21	16.9	31	10
2.1		27		39	12

: Figure 4.3.7; imagined 28Day Stress Relationship

Table 4.3.8projected Values

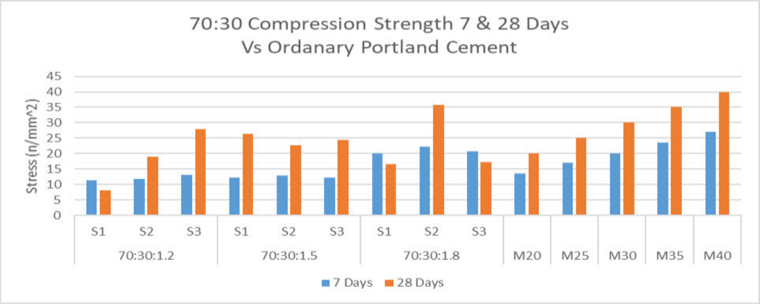


Figure 4.3.9; 70:30 7&28 Day compression Strength histogram

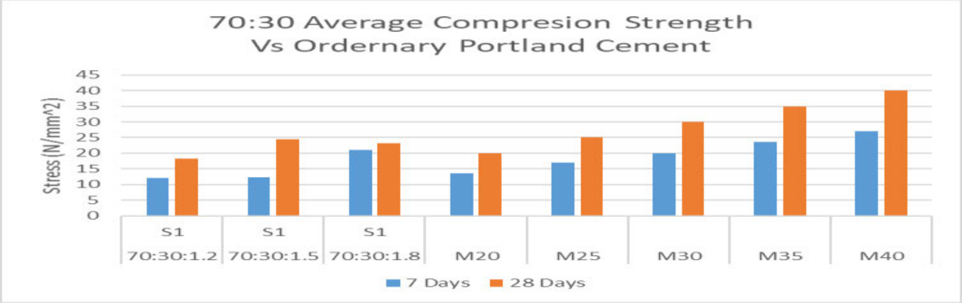


Figure 4.3.10; 70:30 7 &28Day Average Compression Strength Histogram

When looking at figures 38 and 39 above, they show no discernible pattern, but when the hypothesised result values are placed in the table below, a definite cause and effect relationship is visible. It must be stressed this is just an observation with no tangible evidence, but it is intriguing enough to warrant more research.

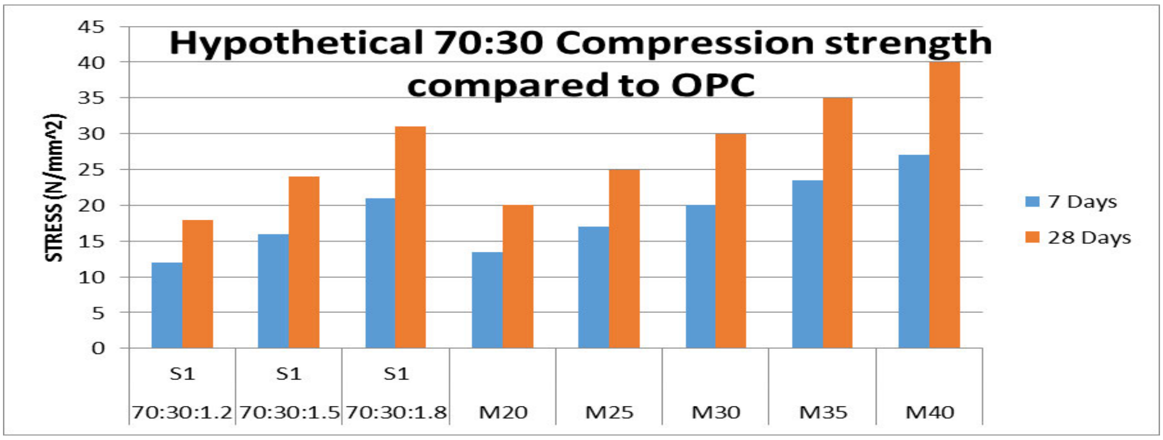
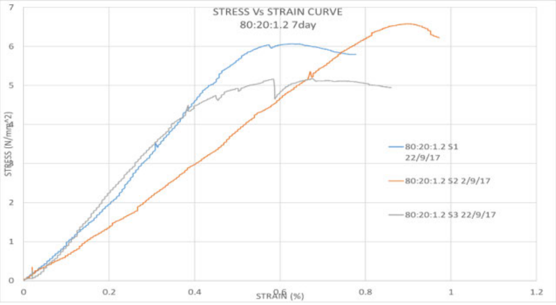


Figure 4.3.11; imagined 7/ 28 day relationship

4.4.1 80:20 compressive strength

7 Days



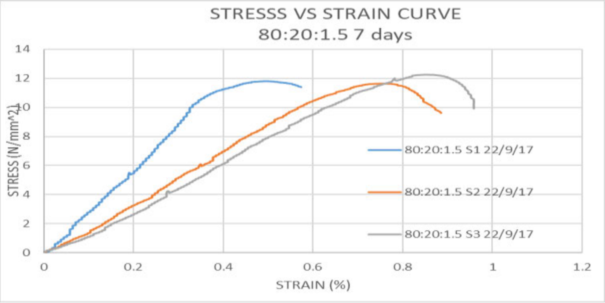


Figure 4.4.1; 80:20:1.2 7Day Compression Strength

Figure4.4.2; 80:20:1.5 7Day Compression Strength

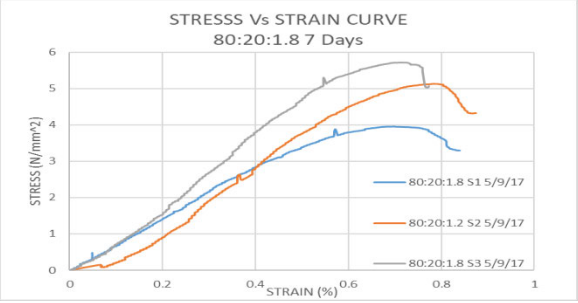


Figure4.4.3; 80:20:1.8 7 Day Compression Strength

7 DAYS								
		STRAIN(%)				STRESS(N/mm^2)		
				Average				
80:20:1.2 12/9/17	S1	MAX	0.777157	0.86983935	S1	MAX	6.06422	5.938298
	S2	MAX	0.972277		S2	MAX	6.579912	
	S3	MAX	0.860085		S3	MAX	5.170763	
80:20:1.5 12/9/17	S1	MAX	0.585859	0.8199145	S1	MAX	11.81149	11.90391
	S2	MAX	0.915545		S2	MAX	11.6487	
	S3	MAX	0.95834		S3	MAX	12.25154	
8020:1.8 5/9/17/	S1	MAX	0.903486	0.94299062	S1	MAX	3.963336	4.937429
	S2	MAX	1.073673		S2	MAX	5.13559	
	S3	MAX	0.851812		S3	MAX	5.713361	

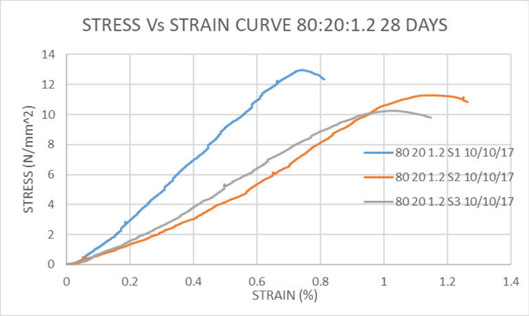
Table 4.4.1 7 Day Stress and Strain

The table of results for the 80:20 7-day mix designs is confusing in the results achieved. Moreover,

1. Due to the lateness of getting the results for this mix design and in the hurry to process the results, an error in the calculations has arisen.
2. For some unknown reason, the higher modulus has resulted in a reduction of compressive strength

At this point, the most likely cultrate must be assumed to be human error.

28Days



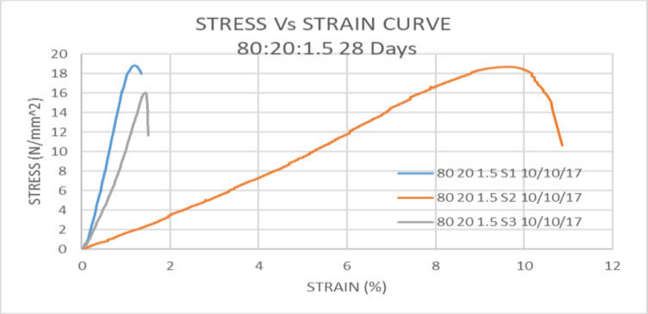


Figure 4.4.4; 80:20:1.2 28 Day Compression strength

Figure4.4.5; 80:20:1.5 28 Day Compression Strength

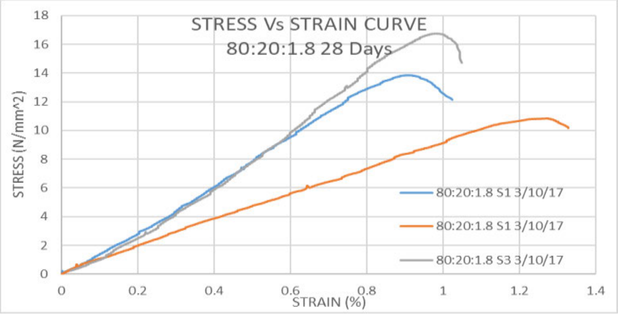


Figure4.4.6; 80:20:1.8 28Day Compression Strength

28 DAYS								
		STRAIN (%)				STRESS (N/mm^2)		
				Average				
80:20:1.2 12/9/17	S1	MAX	0.811768	1.083329	S1	MAX	12.94985	11.495247
	S2	MAX	1.26395		S2	MAX	11.27153	
	S3	MAX	1.174269		S3	MAX	10.26436	
80:20:1.5 12/9/17	S1	MAX	1.347589	4.617913	S1	MAX	18.83197	
	S2	MAX	11.00555		S2	MAX	18.68443	
	S3	MAX	1.500595		S3	MAX	16.01079	17.842396
8020:1.8 5/9/17/	S1	MAX	1.025028	1.135026	S1	MAX	13.83672	13.825547
	S2	MAX	1.336605		S2	MAX	10.8647	
	S3	MAX	1.043444		S3	MAX	16.77522	

Table 4.4.2; 28 Day Stress Strain Data

The results again mirror the seven-day results, even to the reduction in compressive strength of the 80:20:1.8, average compression strength. As the likely hood of the increased modulus weakening the compressive strength as it did not happen to the 70:30 design mixes, the most probable conclusion must be that there was an error in the casting. Assuming this to be accurate and using forward differentiation on recasting the 80:20:1.8 mix design seven-day strength of around 17MPA and 28-day strength of around 23 MPA could be expected. Again, it must be stressed this is just an observation with no tangible evidence, but the possibility it is intriguing enough to warrant more research.

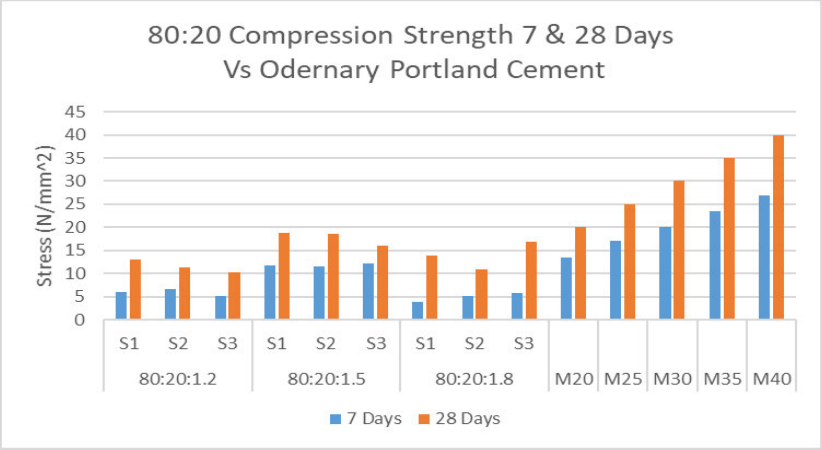


Figure4.4.7; 80:20 7&28 Day compression Strength Histogram

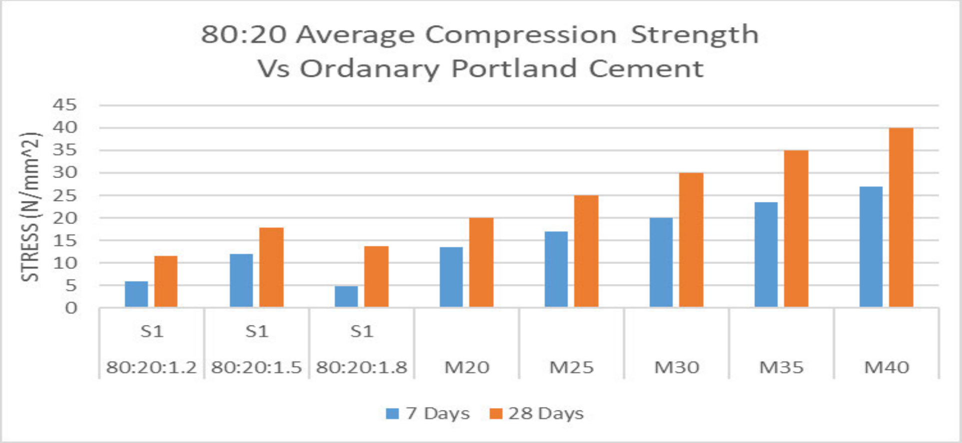


Figure 4.4.8; 80:20:7 & 28 Day Average Compression Strength Histogram

Using the logic applied to the Last Modulus calculations if it is assumed that the 1.8 modulus if incorrect and install the predicted results a cause and effect ratio can be determined.

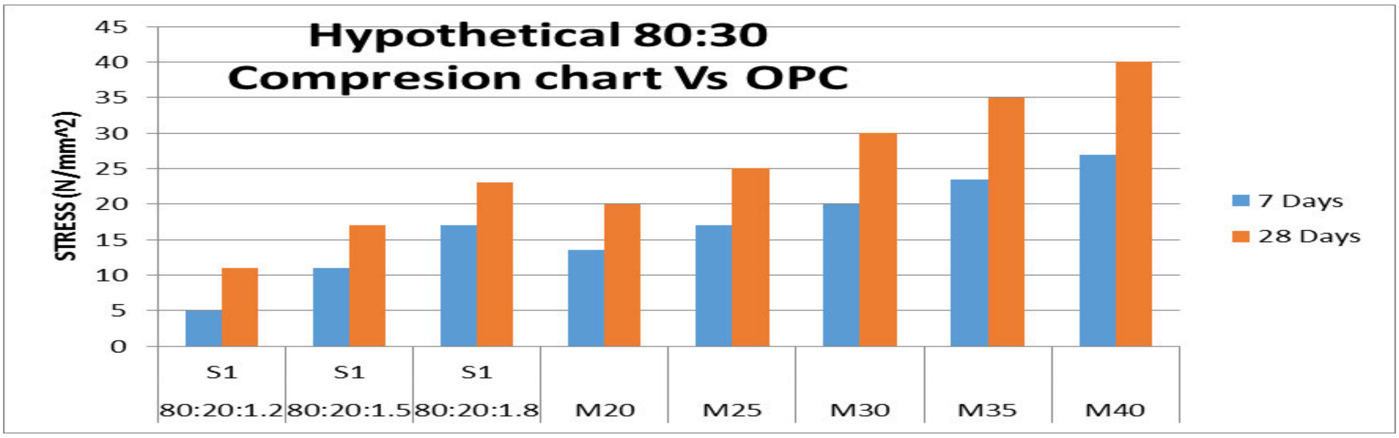


Table 54.4.9; Envisioned 7 and 28 Day Potential Values

4.5 Modulus of Elasticity

				Ec = 5050*√fcm								
Mix			**7 Days**				**Mix**				**28Days**	
Fly-Ash/blast furnace slag ratio	**binder modulus**	**sample number**	**max stress**	**Mean Max Stress**	**Modulus of Elacticity (Ec)**		**Fly-Ash/blast furnace slag ratio**	**binder modulus**	**sample number**	**Max Stress**	**Mean Max Stress**	**Modulus of Elacticity (Ec)**
			N/mm^2	**N/mm^2**	**N/mm^2**					**N/mm^2**	**N/mm^2**	**N/mm^2**
80:20	**1.2**	**1**	6 06422	5.938298	12306.15503		**80:20**	**1.2**	**1**	12.94985	11.495247	17121.84387
		2	6.579912						**2**	11.27153		
		3	5.170763						**3**	10.26436		
	1.5	**1**	11.81149	11 90391	17423.53271			**1.5**	**1**	18.83197	11.565074	17173.76778
		2	11.6487						**2**	18.68443		
		3	12.25154						**3**	16.01079		
	1.8	**1**	3.963336	4.937429	11221.26447			**1.8**	**1**	13.83672	13.8255466	18777.27356
		2	5.13559						**2**	10.8647		
		3	5.713361						**3**	16.77522		
70 : 30	**1.2**	**1**	11.31535	12 03488	17519.11959		**70 : 30**	**1.2**	**1**	8.156227	23.4059842	24431.76442
		2	11.77971						**2**	18.97659		
		3	13.00959						**3**	27.83538		
	1.5	**1**	12.24255	12.3684	17760.20916			**1.5**	**1**	26.39654	24.5146155	25003.67936
		2	12.76422						**2**	22.73794		
		3	12.09842						**3**	24.40937		
	1.8	**1**	20.06518	21 00503	23144.78082			**1.8**	**1**	16.5472	16.904137	20762.89367
		2	22.24713						**2**	35.82303		
		3	20.70279						**3**	17.26107		

Table 4.5.1; Modulus of Elasticity

5. CONCLUSIONS AND DIRECTION FOR FUTURE RESEARCH

With the failure of so many samples, it is difficult to draw any tangible and quantifiable results. Using the logic expressed within Chapter 6 (results and discussion), When it came to possible explanations of the available test results, the indications are that the compression strength has a potentially predictable cause and effect relationship with the modulus, as the modulus increases the compressive strength of the mix design increases. While due to the lack of reliable data this is purely a theoretical hypothesis, it does present an exciting avenue for a future research project

Reflecting on the research project, many valuable learning points were identified and noted for future work.

1. Never assume a timetable, always clarify and check that the time frame established is envisioned is possible and agreed with by all parties involved. It was thought, (from comments made), that materials needed for the project were readily available, with procurement only taking a few days, schedules and bookings were thrown out of kilter when procuring the necessary materials took over a month.
2. Always have an extra person, having an extra person when doing the first run through an experiment this allows flexibility helping to maintaining the necessary experiment time line. When you are unfamiliar with the process things will take longer than envisioned, having an extra pair of hand may save an experiment.
3. When doing multiple samples always number in order of casting to allow the time to be considered as a possible factor later when looking at results.
4. Organisation is Key, a dry run or a rehearsal of all the steps before actually doing the testing for the first time can save a lot of confusion in the long run.

The results of this project have relied on an amount of logic projections to arrive at a viable hypothesis, while this has provided a defendable conclusion for my study it has presented an opportunity to supply a possible prediction to the results to evaluate the next researcher’s investigation into differing modulus.

With this in mind the most interesting opportunity for future research is for the work taken here to be redone and adding another modulus of 2.1 to see if the hypothesised results will stand up to closer scrutiny. The next step after that would be to either see of this holds when using a chemical other than Sodium Hydroxide will supply the same results, or maybe test the results against a modulus greater than 2.2 of sodium silicate, testing to evaluate if the results will follow the same trend.

There seems to be a decided problem when it comes to quality of samples, possibly further research could be undertaken into testing different casting methods for geopolymer cement to find the best way to get uniform results. The possibility of different rodding schedule or using a needle vibrator to achieve perfect compaction of test samples

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APPENDIX 1

Appendix 1Lab procedure

All tasks are written as a stand-alone task, each job starts with putting on correct PPE and ends with removing PPE

Mixing of chemical ingredients

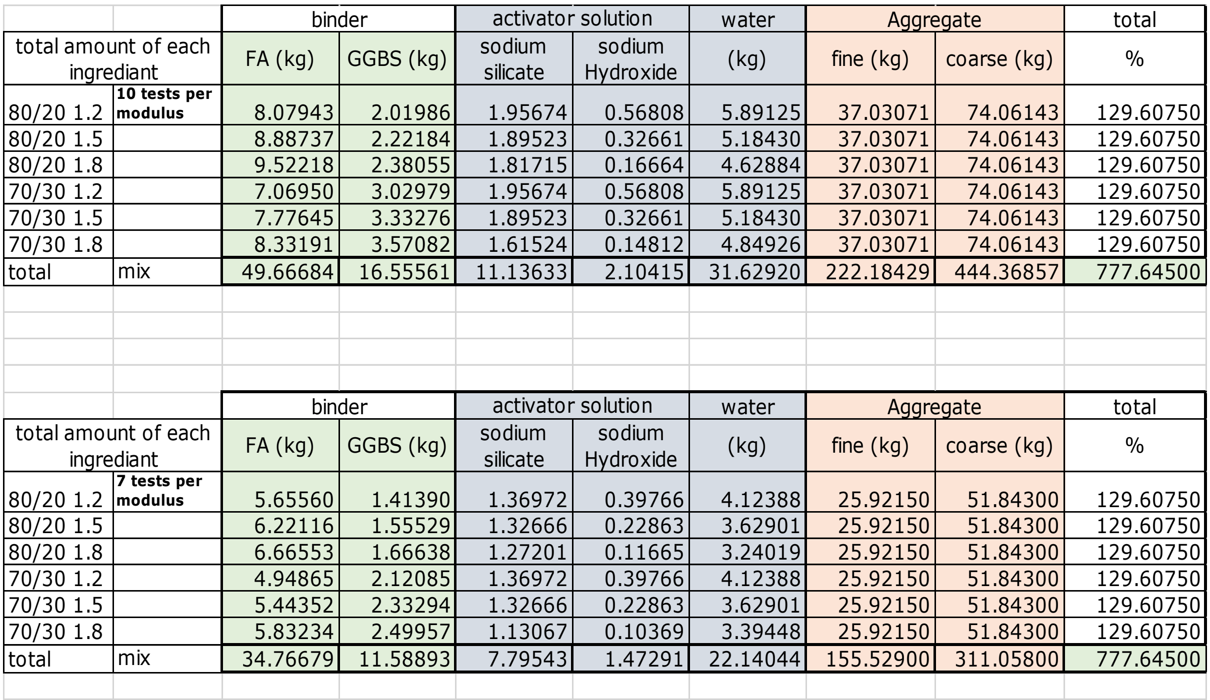
1. Insure all people present have logged only lab attendance sheet.
2. Get all equipment ready for use and insure it is clean and suitable for use.
3. Check the mix batch number and amounts required
4. Check if enough resources are available
5. Zero scales. (Place dish on scales before turning on and it should automatically zero. Should read zero with dish on)
6. Put on all PPE; dust mask, long sleeved shirt and trousers/lab coat, enclosed shoes, chemical resistant gloves and face shield/safety glassed.
7. Turn on extraction fan
8. Measure each chemical in turn, add chemicals to you reach desired weight (do not remove down to weight as will give false reading).

Hydrating of dry ingredients

9. After chemical weighed add to the mixing container.
10. Weigh water (1 kg water is almost exactly 1 litre)
11. Slowly add water to dry ingredients, and gently stir.
12. Clearly label mixing container and allow to rest/dissolve over 3-4 days.
13. Clean down all benches, wash any equipment used sweep and mop floors
14. Remove PPE

Transporting of dry ingredients

1. Place on chemical resistant gloves and eye protection
2. Check binder mix batch
3. Keep container sealed
4. Place binder solution on a transporting trolley.
   (Can be sourced from faculty services or reception A building)
5. Wheel trolley to Engineering labs using the lesser travelled route behind the Auditorium
6. Place container beside bench (out of possible tripping hazard)
7. Remove PPE



		binder		activator solution		water	Aggregate		total
total amount of each ingrediant		FA (kg)	GGBS (kg)	sodium silicate	sodium Hydroxide	(kg)	fine (kg)	coarse (kg)	%
80/20 1.2	**10 tests per modulus**	8.07943	2.01986	1.95674	0.56808	5.89125	37.03071	74.06143	129.60750
80/20 1.5		8.88737	2.22184	1.89523	0.32661	5.18430	37.03071	74.06143	129.60750
80/20 1.8		9.52218	2.38055	1.81715	0.16664	4.62884	37.03071	74.06143	129.60750
70/30 1.2		7.06950	3.02979	1.95674	0.56808	5.89125	37.03071	74.06143	129.60750
70/30 1.5		7.77645	3.33276	1.89523	0.32661	5.18430	37.03071	74.06143	129.60750
70/30 1.8		8.33191	3.57082	1.61524	0.14812	4.84926	37.03071	74.06143	129.60750
total	mix	49.66684	16.55561	11.13633	2.10415	31.62920	222.18429	444.36857	777.64500

		binder		activator solution		water	Aggregate		total
total amount of each ingrediant		FA (kg)	GGBS (kg)	sodium silicate	sodium Hydroxide	(kg)	fine (kg)	coarse (kg)	%
80/20 1.2	**7 tests per modulus**	5.65560	1.41390	1.36972	0.39766	4.12388	25.92150	51.84300	129.60750
80/20 1.5		6.22116	1.55529	1.32666	0.22863	3.62901	25.92150	51.84300	129.60750
80/20 1.8		6.66553	1.66638	1.27201	0.11665	3.24019	25.92150	51.84300	129.60750
70/30 1.2		4.94865	2.12085	1.36972	0.39766	4.12388	25.92150	51.84300	129.60750
70/30 1.5		5.44352	2.33294	1.32666	0.22863	3.62901	25.92150	51.84300	129.60750
70/30 1.8		5.83234	2.49957	1.13067	0.10369	3.39448	25.92150	51.84300	129.60750
total	mix	34.76679	11.58893	7.79543	1.47291	22.14044	155.52900	311.05800	777.64500

Table A1.1; 7 and 10 cylinder mix amounts by weight

Mixing of cement

1. Put on correct PPE, long sleeved shirt and trousers, steel capped shoes, chemical resistant gloves and face shield/safety glassed
2. Insure that all equipment is available and correctly/safely positioned
3. Weigh out all ingredients first; CA, FA, FLA, GGBS. And insure there is sufficient for batch.
4. Add CA and FA and allow to mix 1-2 minutes
5. Add FLA and GGBS to mix and allow to combine with aggregate for 2 minutes.
6. Add wet ingredients,(binder solvent) , and min 2 minutes
7. Allow to sit 2 mins,(aids in the mixing of wet and dry ingredients)
8. Mix for a further 1-2 mins
9. Do slump test

Slump testing

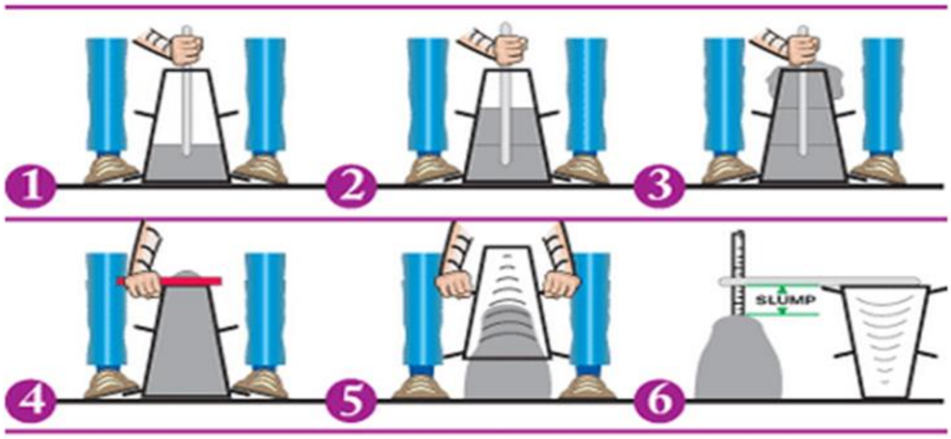


Figure A1.2; how to do slump test

WHY.

The slump test is done to determine the workability, (or how easily it flows), of the concrete mix by examining the consistency of the concrete. A slump test is done to ensure uniformity between different loads of concrete under field conditions.

1. Ensure that slump cone is clean and has been oiled

2. Clean and dampen a flat ridged surface (floor) for the test.

3. Place the metal mould (known as the slump cone or Abrams cone), large opening down, (it is open at both ends), on the surface

4. Fill each cylinder 1/3 full and rodded 25times, with a 10mm diameter steel rod with a hemispherical tip and be between 450-600 mm in length. The strokes will be evenly distributed over the entire cross sectional area of the test cylinder.

(Important: the rod must not be allowed go all the way through the mix and strike the bottom of cylinder)

5. Fill cylinder to approximately 2/3 full and rodded 25 times. Ensure that the rod only penetrates 25mm into the lower layer. Ensuring even distribution of rodding over entire cross section.

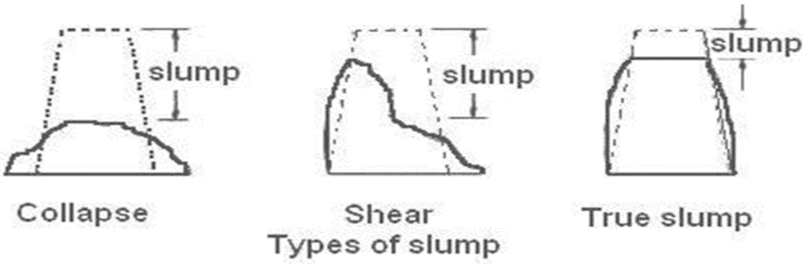
6. Fill cylinder to full and rod 25 times. Ensure that the rod only penetrates 25mm into the lower layer. Ensuring even distribution of rodding over entire cross section.

7. Cast smooth the top of layer after rodding and ensure level top surface.

8. The mould is then removed vertically, minimizing the disturbance of the sample.

9. The mould is then placed beside the test mix

10. When the mould is removed, the concrete will slump under its own weight; the height between the top of the mould and the top of the concrete is measured in millimetres within 2 minutes of sampling. This distance is referred to as the slump of the mix



Types of slump

The slump of the concrete takes on three different profiles;

Collapse- this indicates that the sample is too wet or has a high workability, and not suitable for a slump test.

Shear – this usually indicates one of three (3) things, Firstly, the sample was disturbed by the mould during removal or; secondly, The mix is too dry, (this could also give a zero slump); and lastly the mould was not properly cleaned and oiled before the sample was tested

True slump- this is how a slump sample should look and is indicative of an accurate reading.

Casting test cylinders

Every sample will be cast in a 100mm x 200mm non-absorptive metal Cylinder mould and will be carried out following industry standard testing procedures.

Ensure every test cylinder is clean and has been pre-oiled

Every cylinder to be placed on a dampened, smooth, firm, level and non-absorptive surface. (Damping the surface stops spilled mix drying and sticking to surface before clean up)

Fill each cylinder 1/3 full and rodded 20 times, with a 10mm (25 times if using 150mm cylinders), diameter steel rod with a hemispherical tip and be between 450-600 mm in length. The strokes are to be distributed evenly over the entire cross sectional area of the test cylinder.

(Important: the rod must not be allowed go all the way through the mix and strike the bottom of cylinder)

Fill cylinder to approximately 2/3 full and rodded 20 times. Ensure that the rod only penetrates 25mm into the lower layer. Ensuring even distribution of rodding over entire cross section.

Fill cylinder to full and rod 20 times. Ensure that the rod only penetrates 25mm into the lower layer. Again ensuring even distribution of rodding over entire cross section.

Cast smooth the top of layer after rodding and ensure level top surface. (Recommended that the side of cylinder is GENTLY tapped 3-4 times to close any voids in the test cylinder)

Cover top of each test cylinder with cling film and sealed with a rubber band, or place in a plastic bag and sealed to ensure that there is no loss of moisture.

Test samples are to be left in the moulds for a minimum of 28 ± 8 hrs before being de-moulded. They are then to be placed on a rigid flat, stable surface to allow them to harden enough to withstand handling, (samples are to be kept clear of any vibrations as this will affect the samples and supply false test results). Test cylinders need to be kept in a temperature controlled environment, (constant temperature of between 20 ± 5 Co)

Clean mixer and any tools used, when cleaning empty mixer slurry into a container and allow to settle. Empty water onto ground and place solid waste into a bag for disposal in a bin.

Clean down all benches, wash any equipment used sweep and mop floors

Remove PPE

Demolding of cylinders

When the samples have been de-moulded (after 20 hrs), they will be wrapped in a plastic film to maintain the moisture and they will then be moved to a storage location and kept at a constant temperature of 20 ± 5 Co .

Put on correct PPE, safety boots and work gloves

Make sure space for the samples is ready to receive them.

Place all samples and equipment is on bench ready to proceed

Remove sample from the mould and prepare it for curing.

Curing of cylinders

Ensure steel capped boots and gloves are worn when handling samples.

Check batch label

Wrap each sample in cling wrap to prevent loss of moisture and label each sample with the batch number and testing date.

Clean and re-oil all cylinders

Remove PPE

Concrete density testing

The first test done on each batch will be a density test, this is a quick non-destructive test that can be quickly carried out on a sample and will give a good idea of the volumetric quality =of the sample and the air content of the sample. If the density between two samples differs, it is also a good indicator that one of the samples may be faulty.

The sample is weighed and divided by the volume of the sample giving the density of the sample .ρ = Mass/Volume ≡ ρ= (4*mass)/ (π*D^2*h)

Put on PPE

Weigh sample and record on result sheet

Do the simple calculation above

Record density

Remove PPE

Check for shrinkage

On the day of testing measure the diameter of the cylinder approx. 1/3 from top and 1/3 from bottom of sample to ensure symmetry

Put on PPE

Using Vernier Callipers measure cylinder diameter 1/3 from top and then 1/3 from bottom

Record results on sheet

Remove PPE

Mechanical Analysis (destructive testing)

Compressive Strength

Each of the design samples will be tested for compressive strength at 7, 14 and 28 days. By doing this, we will hope to be able to graph the results and visualize how the different mix designs are affected by the changing binder modulus and concentrations and hopefully be able to predict the results of mixes inside and outside the test range.

By testing at different cure times, it will give an accurate gauge of curing times and determine when the design reached full strength.

The compression test follows the following steps.

Put on all safety gear PPE at this point.

Record sample mass and sample number.

Record density of each sample.

Cap each sample pad cap to ensure even load distribution.

Measure the sample diameter in two locations, if these measurements differ by more than 2%, the sample should not be tested.

Centre sample on the testing machine

Lower piston to the top of the concrete sample without applying load. Check position and stability.

Put the machine in holding position and zero gauge.

Apply pressure without shock, adjust pressure until piston pressure matches compression strength.

Observe sample, when it begins to break stop applying pressure.

Record reading

Clean machine of any concrete before starting next test.

Calculate concrete strength

All tests will be done in accordance with Australian Standards AS 1012.12.1, Method for Testing Concrete

Appendix 2 Risk assessment

The potential risks associated with this research project were identified and classified in accordance with the, Queensland Government Department of Occupational Health and Safety Guide for Risk Assessment, (Aug 2012),[This is considered an industry standard in the identification, understanding and evaluation of the risk of work related injury], and the USQ Safety Risk Management system.

Measurement of the likelihood of happening

Rating	**Description of likelihood**
Almost certain	The event is *expected* to occur in most circumstances
Likely	The event will *probably* occur in most circumstances
Moderate	The event s*hould* occur at some time
Unlikely	The event *could* occur at some time
Rare	The event *may* occur but only in exceptional circumstances

Table 6: OH&S Likelihood of Occurrence

Consequence of Occurring

Consequence	Description of consequence
Insignificant	No Treatment required
Minor	Minor Injury- Requiring basic first aid treatment(e.g. minor cut ,Bruise)
Moderate	Injury will require medical treatment of loss of production time
Unlikely	Serious injury requiring specialist treatment or hospitalisation
Rare	Injury causing multiple serious injuries, loss of life or permanent disability

Table 7 OH&S description of consequence of accident

Using the two tables above consider the hazard and determine the risk level

Risk Level

Likelihood	**Risk of occurring**				
	Insignificant	**Minor**	**Moderate**	**Major**	**Critical**
Almost certain	Medium	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	High	Extreme
Moderate	Low	Medium	High	High	High
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Low	Low	Medium

Table 8: OH&S Risk of accident

Hazard control

Control methods , (highest to lowest)
Elimination; remove hazard completely from work place
Substitution; replace hazard with a less dangerous one, (replace chemical with less dangerous one)
Redesign; Make machine or process safer for user, (chance bench height).
Isolation; separate hazard for people, (safety barrier).
Administration; Placing signs and instructions, put training in place
PPE; Determine correct safety equipment needed for each task

Table 9; OH&S Hazzard control

Description of risk level

Assessing risk Level	**Description of risk level**	**Action to be taken**
Low	If an accident were to occur, there would be **little likelihood of an injury** occurring	**Undertake this activity with current safety controls in place**
Medium	If an accident were to occur, there would be **some chance of an injury requiring first aid** occurring	**Additional safety controls may be needed**
High	If an injury was to occur it **would be likely that an injury requiring medical treatment** would occur	**DO NOT PROCEED** Safety controls will need to be put into place before this activity is undertaken
Extreme	If an injury was to occur it would be **likely that a permanent, debilitating or fatal injury** would occur.	**STOP** **Consider alternatives to doing this activity** Significant Safety control measures need to be implemented before attempting this activity**.**

Table 10 OH&S Risk description and action required

Safety Analysis of the work to be undertaken

Risk	**Hazzard**	**Consequence**	**Likelihood**	**Risk level**	**Control method**
1 Sharp edges on cut reinforcement mesh	Cut or stab injury	Moderate	Unlikely	Low	Use of correct PPE; safety boots and gloves
2 Splash when mixing formula.	Eye Injury	Moderate	Unlikely	Low	Use of correct PPE; eye protection
3 Penetration from flying concrete shard	Eye Injury	Moderate	Unlikely	Low	Use of correct PPE; eye protection
4 Damaged electrical cables and water over floor	Electrocution	Moderate	Unlikely	Low	Keep worksite dry and inspect all electric tools before use
4 Equipment and form work on floor	Tripping	Likely	Minor	Medium	Keep worksite clean and free of hazards. Safety barriers around points of risk
5 Testing equipment	Crush injury	Moderate	Major	Medium	Ensure safety barriers are in place, Follow operators manual. Only operate testing equipment with trained personnel, or after training.

Table 11 OH&S Safety Analysis of Planned Work

Review of safety controls.

After reviewing the safety hazards and the control measures I had planned to undertake, I believe that these safety precautions are adequate and have made the project as safe as possible.

Note

Due to the need to conduct the mixing of the binder agent in the Geopolymer laboratory and mix, construct and test the samples in the Engineering concrete laboratory two different risk management assessments were carried out, one for each laboratory.

Concrete lab Risk Management submitted to project supervisor and approved Geopolymer Lab Risk Management submitted to project supervisor and approved.

Appendix 3 Project Specification

ENG4111/4112 Research Project Project Specification

For	Richard Knight
Title	Development of a low CO2 Durable Concrete Using Geopolymer and Related Chemically-Activated Materials
Supervisors	Dr Hoa Wang Zahua Zhang
Sponsorship	The Nielson Group
Enrolment	ENG4111-ONC S1, 2016 ENG4112-ONC S2, 2017
Project Aim:	This project looks to investigate the use of Fly ash and slag to find a possible suitable replacement for Portland cement under certain applications.
Programme;	Version 1 15 March 2017

1. Review existing data and evaluate the potential and current uses of Geopolymer concrete.
2. Examine current literature to determine a suitable mix ratio for the desired compression strength needed
3. Review current standards to determine the correct testing required to prove the mix potential.
4. Do small test samples to determine sample mixes of potential
5. Do a large-scale mix 30L of the most promising 2 mixes for testing to prove results