Mechanical Properties of Crumb Rubber Geopolymer Concrete

Scott J. Taylor

The University of New South Wales at the Australian Defence Force Academy

Due to the large number of End-of-Life (EOL) tyres being disposed of annually, through landfill, stockpiles and illegal dumping, there is an international need to develop innovative, non-intrusive ways to recycle Equivalent Passenger Unit (EPU) tyres that have reached the end of their usable life. The inclusion of Granulated EOL tyres, in the form of Crumb Rubber (CR), into permanent concrete forms and structures is incipient and a subject of great interest particularly with Geopolymer Concrete (GPC). GPC has shown significant relevance in the emerging construction market which can be attributable to its métier properties, early strength and reduced environmental impact. Research has been conducted into characteristic properties of Crumb Rubber Geopolymer Concrete (CRGPC). However, for CRGPC to establish its permanent place in the construction market, there needs to be consistency in characteristic properties within the same compressive strength category. This will allow designers to select CRGPC for application based on the compressive strength and regardless of the mix composition will deliver appropriate properties (with in a range). Limited studies have been performed to properly establish the characteristic properties of comparable compressive strength CRGPC made with varying quantities of CR as fine aggregate. The aim of this research is to investigate the characteristic properties of different CRGPC design within the same compressive strength category. Experimental research has been conducted to establish the characteristic property effects of adding CR to GPC. This was done by using three different compressive strength GPC mixes and replacing 5%, 10% and 15% of fine aggregate by volume with a well graded crumb rubber mix. Trends from the compressive strengths of these mixes where used to modify the CR additive quantities in order to various mixes with the same compressive strength. The characteristic properties of these mixes were then tested and analysed. The results demonstrated a reduction in the compressive strength when crumb rubber was added to the GPC mix. Comparisons with predictive characteristic property equations from various Standards highlighted a greater than 20% variance for the E_c, which indicates that independent equations need to be developed for CRGPC. Additionally, the results from targeted testing revealed a lower modulus of elasticity with greater CR content between CRGPC's with comparable compressive strengths and densities. Even with significant percentages of CR (35%) design compressive strengths were still achieved (32MPa). CRGPC concrete is suitable for almost any structural and non-structural purposes and could be extremely beneficial for use in applications that require higher energy absorption or deflection characteristics.

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I. Introduction

Hundreds of millions of end-of-life tyres are disposed of every year contributing millions of tons of scrap waste to landfills. Due to the difficulty in the process required to breakdown and separate the components of waste/scrap tyres, only a small fraction of this is recycled. Therefore, their disposal represents a major global problem and a fresh focus needs to be taken with the need and approach to recycling used tyres.

Concrete is the second most widely used material in the world behind water alone. There presents an opportunity to utilise Crumb Rubber (end-of-life tyres) into the form of aggregate within concrete structures. When producing concrete from Ordinary Portland Cement (OPC), the most widely used Cementitious material, a chemical hydration process takes place emitting approximately one kilogram of Carbon Dioxide for every one kilogram of concrete produced. A problem with introducing Crumb Rubber into OPC is that the compressive strength is significantly reduced. Research has been conducted with crumb rubber OPC (Mendis, 2017) that shows that to increase the strength of CRC the quantity of binder must increase. This can essentially negate the environmental benefits of the CR inclusion as the quantity of OPC required for the mix is increased, which introduces additional CO_2 emissions. As an addition hurdle to overcome, CR does not facilitate an effect bond with cement binders due to its surface condition. As such, a pre-treatment is required to roughen the surface of the CR. This entails soaking the CR into an Alkaline solution for 24 hours prior to use. This is where the utilisation of Alkaline Activated Fly Ash (AAFA), as a replacement for OPC, can be of great benefit. Geopolymer Concrete (GPC) utilising alkaline activated Fly Ash (a by-product of coal combustion in power stations) and produces approximately 70% less life cycle greenhouse gas emissions when compared to OPC. Additionally, AAFA requires an Alkaline solution, generally made up of Sodium Hydroxide and Sodium Silicate, to facilitate the chemical process in which a paste capable of setting and hardening is developed. Therefore, pre-treatment of the CR can be performed utilising the Alkaline solutions that are already required for the binder. CRGPC is a relatively new concept and although already in use for bespoke designs, little research has been conducted to establish if CRGPC can be selected using OPC concrete standards or whether separate CRGPC standards need to be developed.

Aim

Experimental research will be utilised to better understand characteristic property changes of Geopolymer Concrete when Crumb Rubber (CR) is used in place of a portion of the fine aggregate. The aim of this project is to determine if the already established standards for representing mechanical properties of OPC Concrete can be used or modified for use with CRGPC. Additionally, establish the effect that CR has on GPC E_c independent of the inherent decrease due reduction of density. This will be achieved through the conduct of experiments in order to document the characteristic properties of different Crumb Rubber Geopolymer Concrete (CRGPC) mixes and compare the properties of similar compressive strength mixes with varying crumb rubber content. Developing trends that occur with the addition to CR to GPC will help to predict GPC behaviour when CR is used and identifying similarities or discontinuities with similar compressive strength CRGPC. This will enable a comparison of CRGPC to the OPC concrete standards and, if needed, aid in establishing new Standards when selecting CRGPC for design purposes.

Methodology and Approach

1. Develop three Geopolymer Concrete (GPC) mixes with varying compressive strengths ranging evenly between 30MPa and 60MPa. Desirably 30MPa, 45MPa and 60MPa. Some possible procedural variables that will remain consistent for all samples including testing period (7-day), room temperature room (23degree C) and oven curing time (72hrs @ 80degree C). It is desirable that the mixes be significantly different in their composition. Due to the compositional complexity of GPC only limited ingredients will be altered to achieve the desired variations. Therefore, for these experiments the GPC ingredients for mix design will fall into the following categories:

Variable:

- Alkaline solution to fly Ash ratio
- Total aggregate content
- Use of single and well-graded course aggregate
- Use of GGBS
- Water content

Fixed:

- Fly Ash source
- Sodium Silicate
- Sodium hydroxide (16M)
- Sodium Silicate/ Sodium hydroxide ratio (2.5)
- Fine aggregate source
- Super Plasticiser (0-1% mass of binder solids)

2. Measure and record key characteristic properties (Compressive strength, elastic modulus and flexural strength) of each of the three reference GPC mixes.
3. Perform a sieve analysis of crumb rubber and develop a Particle Size Distribution (PSD) curve using different crumb rubber sizes (<1mm, 1-3mm and 2-4mm) to match that of the fine aggregate (sand) that is being used in the GPC mix designs.
4. Take each of the three reference GPC mixes and replace a percentage of the fine aggregate with Crumb Rubber (CR) creating Crumb Rubber Geopolymer Concrete (CRGPC). These percentages will be 5%, 10% and 15% for each of the reference mixes.
5. For each of the CRGPC specimens measure and record key characteristic properties.

6. The data from the experiments will then be analysed and any trends identified will be used to create different CRGPC mixes that have similar (within 5%) compressive strengths.
7. The key characteristic properties will then be measured and compared.

II. Literature Review Summary

GPC has been receiving extensive research owing to is métier properties over Ordinary Portland Concrete (OPC). Adding to the environmental and cost benefits, GPC also consisting of lower creep, lower shrinkage, better fire and acid resistance, and resistance to sulfate attack (Vargas, 2011).

Interfacial bonding between crumb rubber aggregate and cement paste possess a problem due to the smooth surface of the rubber particles. Chemical pretreatment of rubber improves adherence and mechanical resistance compared with rubber concrete without pretreatment (Roman Chylík, 2017). There are many proven pre-treatment processes however, NaOH aqueous solution pre-treatment has returned favourable results obtaining a high strength performance (D. Raghavan, 1998). This represents great relevance to the aim of this research.

Standards exist to predict the tensile strength and E_c of OPC based on the compressive strength (Mendis, 2017). Splitting tensile strength of GPC has been found, through experimental models (E. Ivan Diaz-Loya, 2011), to be similar to the equation given by ACI 318-11, for OPC to estimate the modulus of elasticity:

$$f_{ctm} = 0.556\ (f_c')^{0.5}\ MPa \qquad \text{(ACI Committee 318-11, 2011)} \qquad \text{Equation 1}$$

$$f_{ctm} = 0.59\ (f_c')^{0.5}\ MPa \qquad \text{(ACI Committee 363-92, 1992)} \qquad \text{Equation 2}$$

$$E_c = 4733\ (f_c')^{0.5}\ MPa \qquad \text{(ACI Committee 318-08, 2008)} \qquad \text{Equation 3}$$

Where f_{ctm} is the tensile flexural strength and f'_c is the compressive strength of OPC concrete after 28 days of curing. A crude analysis could be made that f_{ctm} is approximately 8-10% of f'_c at 7-day strength for GPC. GPC mixes can exhibit a wide range of density values depending on the Fly Ash fitness and therefore a wider range of E_c is noticed. An experimental interaction between the density and the compressive strength of GPC can give a predictor of the elastic modulus as researched in (Jannie S.J. van Deventer, 2012) & (Mendis, 2017):

$$E_c = 33(w)^{1.5}\ (f_c')^{0.5}\ KPa \qquad \text{(ACI Committee 318-11, 2011)} \qquad \text{Equation 4}$$

$$E_c = 0.043(w)^{1.5}\ (f_c')^{0.5}\ MPa \qquad \text{(AS 3600, 2009)} \qquad \text{Equation 5}$$

Equations 1-5 will be used in comparison to the experimental empirical values obtained and analysis carried out to determine their applicability to CRGPC.

Experimental research on GPC has previously been conducted replacing various percentages of aggregate with crumb rubber. Results indicated that the compressive strength decreased as the rubber content increased however, the mixtures demonstrated a ductile failure. The compressive strength of CRGPC mixtures are affected by the size, proportions, and surface texture of the crumb rubber particles, and mix composition of the bonding material. In addition, the failure of the samples also due to the crumb rubber being more elastically deformable than the matrix (Ahmad Azrem Azmi, 2016). The complete Literature Review can be found in *Appendix O*.

III. Experimental Research

Preparation

Due to the inconsistent nature of Fly Ash from bag to bag, trial mixes were returning erroneous results when replicating mix designs. From these results it was ascertained that the data sheets from the suppliers were not able to be used. To alleviate this problem a large container (1000L) was obtained and half filled with Fly Ash, this was all then hand mixed together. By performing this process Fly Ash bags with higher calcium oxide and lower pozzolanic contents were mixed with Fly Ash bags with more desirable characteristic. This yielded a consistent product to be used for research purposes although, the actual chemical composition of the product used could only be determined if an analysis was performed.

The 16M sodium hydroxide solution was prepared by dissolution of NaOH pellets in water using 0.444kg/kg solution (Junaid, 2015). All containers were kept sealed when they were not in use to minimise contamination by atmospheric carbonation.

Particle Size Distribution

In order to use the Crumb Rubber as a volumetric replacement, for the fine aggregate (Riverbed Sand), it is required to ensure the crumb rubber mixture is graded within the limits set out in the Australian Standards for well graded fine aggregate. The Crumb Rubber being used for this research was sourced from mechanically shredded waste truck tyres. Three different particle sized CR, <1mm, 1-3mm and 2-4mm, were mixed together in the ratio 8/7/5 respectively (*see Appendix I Figure I7*) and a sieve analysis was carried out (AS 1141.0-1999, 1974) to produce a Particle Size Distribution Curve. *Figure I8* demonstrates the sieve analysis results for the mix design Riverbed Sand and Crumb Rubber. The upper and lower limits are shown signifying the materials fall within requirements for well graded fine aggregates.

Crumb Rubber Pre-treatment

To enable the crumb rubber to have adequate bonding with the geopolymerised paste the CR must first be pre-treated. Placing the CR into a Sodium hydroxide solution for 24 hours prior to creating the mix roughens the rubber surface creating suitable surface for the paste to bond to. An issue with this process is created by the different in density of the CR and the Sodium Hydroxide causing the CR to remain unsubmerged into the solution. To overcome this the CR is placed into a container with stainless steel gauze on top, the Sodium Hydroxide is then poured onto the CR. The Sodium Hydroxide then seeps through the gauze completely submerging the CR particles. This ensures the CR remains submerged for the entire 24-hour period. Using the quantity molar density (16M) of Sodium Hydroxide required for the mix makes the process easy and waste free.

Mixing

Due to the inconsistent compositional nature of commercial Fly Ash, three individual and distinguishable mix designs (*Table 1*) of different compressive strengths were designed. This enable consistent and repeatable mix results to carrying out the investigation.

Table 1. Core Mix Designs (kg/m^3)

Materials	Detail	GPC30	GPC46	GPC58
Fly Ash		445.76	386.65	360.00
Sodium Hydroxide		63.68	41.00	49.00
Sodium Silicate		159.20	103.00	122.50
Water		48.28	66.09	50.38
Fine Aggregate	Riverbed Sand	571.18	555.00	535.00
Coarse Aggregate	7mm	0.00	0.00	245.00
	10mm	1243.10	1295.00	430.00
	14mm	0.00	0.00	555.00
GGBS		0.00	20.35	40.00
Super Plasticiser		6.73	0.00	0.00

CR mixes were made by replacing 5%, 10% and 15% by volume of the fine aggregate for each of the core mix designs. All other material quantities remained the same as the core mix. Weight of crumb rubber was calculated using a ratio of the specific gravity of the crumb rubber (1.15) to the fine aggregate (2.6) *Table 2*.

Table 2. Crumb rubber addition Quantities

	Fine aggregate	Crumb Rubber
CR5GPC30	542.62	12.63
CR10GPC30	514.06	25.26
CR15GPC30	485.50	37.90
CR5GPC46	527.25	12.27
CR10GPC46	499.50	24.55
CR15GPC46	471.75	36.82
CR5GPC58	508.25	11.83
CR10GPC58	481.50	23.66
CR15GPC58	454.75	35.50

Curing

Curing took place both at 23°C (room temperature) and in an 80°C oven. Once placed into the mould all samples were first placed into a 23°C room for 24 hours. Depending on the mix design samples were then moved to the 80°C oven for between 72 hours. On completing of the oven curing samples were then returned to the 23°C room for the remained of the sevens days until testing was carried out.

Testing

Testing for mechanical properties (Modulus of Elasticity, Compressive Strength and Indirect Tensile Strength) was carried out in accordance with:

Determination of Static Chord Modulus of Elasticity and Poisson's Ratio of Concrete Specimens (AS 1012.17, 1997).

Determination of the Compressive Strength of Concrete Specimens (AS 1012.9, 2014)

Determination of Indirect Tensile Strength of Concrete Cylinders (AS 1012.10, 2014)

Rationalisation of Testing method and procedure

Samples were labeled according to their base GPC mix compressive strength and the percentage of crumb rubber additions made to that base mix.

Examples:	CR5GPC58	5% Crumb Rubber in a base mix of 58MPa GPC
	GPC30	0% Crumb Rubber in a base mix of 30MPa GPC

Three different mix design were used in order to understand the effect that crumb rubber has on Geopolymer concrete when added as percentage replacement of the fine aggregate. To develop the appropriate breadth of mix design, variables included quantities of all mix elements, using different coarse aggregate sizes (well graded and single graded), the addition of super plasticiser and ground granulated blast furnace slag. This provided a good sample spectrum to base this research on.

GPC can form quite a strong bond to conventional standard cylindrical ($\phi\ 100mm \times h\ 200mm$) molds when set. This can make it extremely difficult to remove the cured samples from the molds resulting in either damaged or distorted samples. Additionally, the removal process can be time consuming especially when dealing with large quantities of samples (for example 24 at a time). Specialised plastic molds were used in order to produce the samples to eliminate both the potential for damage and the time intensive process of sample removal. These specialised molds (FORNEY Concrete cylinder molds) were difficult and expensive to acquire as they required shipping from the United States. As such, an alternative specialised mold was developed in order to complete the required testing. These alternative molds consisted of 100mm diameter PVC piping (rated for 80°C) cut into 200mm lengths with a fitted 100mm diameter cap for the base. This enable the completion of testing at a much cheaper rate and where readily available as they could be produced within the workshop using locally sourced materials.

Three samples were subjected to each of the three testing methods, Compressive, Modulus of Elasticity (non-destructive) and Indirect Flexural Strength. Six samples of each mix design were developed in order to perform the testing necessary to deliver the characteristic properties that were required analysis. Three samples where used for compressive testing, the results from which were used to analysis the E_c of the remaining three samples by cyclic loading at 40 percentage of the ultimate compressive strength. As these samples were not damaged during modulus testing, they were used again for the Indirect Flexural analysis. Nine samples could have been used however due to the non-destructive modulus testing only loading to 40 percent there is expected to be little to no residual effects on the samples. Using this method enable less samples to be produced, which ultimately resulted in using less material and specialised plastic molds which can be expensive and wasteful. Results from each of the three samples for each of the test is averaged to produce the characteristic properties for each mix design. This allows for either the removal of any extreme outlier results or as a minimum reduces the effects of any non-conforming result from any one specimen.

Three measurements were taken, for volume and density, from different locations and orientations of the samples and an average figure developed. This made allowances for any inconsistencies that may have developed in the sample due to the plastic molds, the heating and de-molding process.

Testing was carried out using 40 percent of the ultimate compressive strength and applied through four loading cycles whilst using linear variable differential transformers to monitor for deflections. The first cycle was ignored to allow for settlement within the samples. The linear portion of the stress/strain slope of the remaining three cycles where then taken and averaged to develop the samples E_c.

The initial percentage quantities for substituting crumb rubber as a portion of the fine aggregate where determined using previous experiments carried out by various authors on both GPC and OPC. Using 5, 10 and 15 percent appear to have a sufficient difference in results without leaving any characteristic property trend gaps that may occur as a result of the crumb rubber substitution. Once the core CRGPC mixes had been established and tested the results were plotted on an excel spreadsheet and linear and nth order polynomial traces added. This enabled the prediction of the possible quantities of fine aggregate to be substituted for crumb rubber in order to achieve a desired ultimate compressive strength.

Indirect tensile testing of cylindrical specimens was selected over the flexural tensile strength test in order to keep the production and testing process simple. Although the Indirect tensile test method is not as accurate the results are sufficient for the purpose of this investigation. Any benefits in accuracy that flexural tensile strength testing yields are inconsequential to the outcome of this research as the samples are being compared to each other therefore if the same process is used there is consistency within the testing system.

IV. Results

Crumb Rubber Pre-treatment

Results of pretreating CR with sodium hydroxide (16M) for 24 hours prior to use in CRGPC mix

Figure 1. CR vs NaOH Pre-treated CR (Full particle)

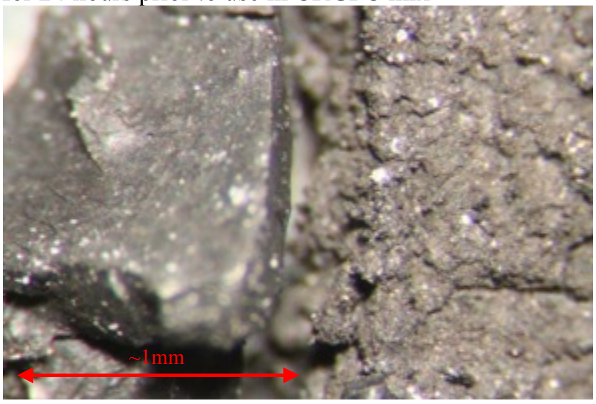

Figure 2. CR vs NaOH Pre-treated CR (Half particle)

Core Mix and 5%, 10% and 15% Sample Test Results

Table 3. Experimental Results Crumb Rubber 0%, 5%, 10%, 15%

Mix	Density (kg/m^3)	Compressive Strength (MPa)	Modulus of Elasticity (MPa)	Ind Tensile Strength (MPa)
GPC30	2252.25	29.96	15886.75	2.77
GPC46	2272.77	46.04	22524.91	3.75
GPC58	2263.07	57.49	24634.41	4.55
CR5GPC30	2216.35	25.91	14088.35	2.49
CR10GPC30	2200.23	25.71	13801.26	2.46
CR15GPC30	2169.56	23.45	12829.36	2.30
CR5GPC46	2249.90	41.55	20238.84	3.31
CR10GPC46	2234.41	37.01	18801.69	3.13
CR15GPC46	2214.95	34.06	19777.47	3.79
CR5GPC58	2270.30	45.27	25250.64	3.83
CR10GPC58	2257.91	42.88	22646.33	3.69
CR15GPC58	2250.55	50.80	23793.22	5.03

Additional Mix Test Results

Table 4. Experimental Results CRGPC Additional Mixes

Mix	Density (kg/m^3)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Ind Tensile Strength (MPa)
CR5GPC30	2216.35	25.91	14088.35	2.49
CR20GPC46	2184.56	33.53	17705.88	3.10
CR25GPC46	2174.90	30.49	16104.79	3.07
CR30GPC58	2182.95	34.19	18495.55	3.21
CR35GPC58	2170.24	32.75	15733.63	3,41

Graphical Representation of Core Mix and 5%, 10% and 15% Results.

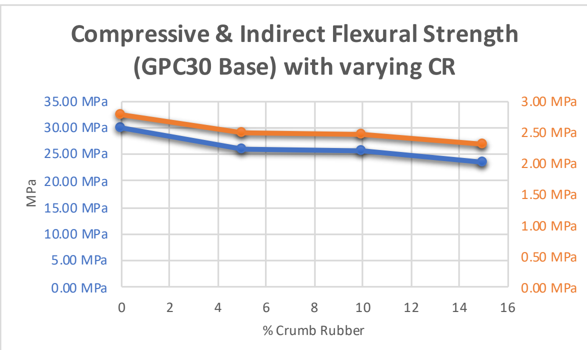

Figure 3. Compressive & Indirect Flexural Strength of CRGPC30

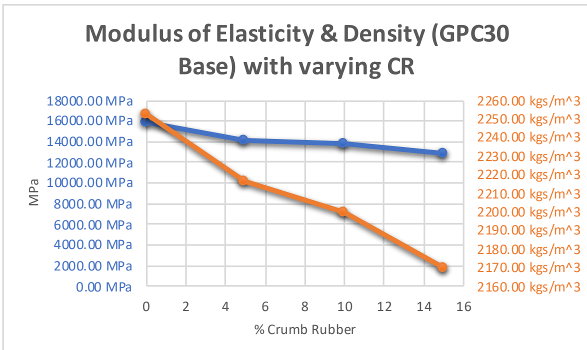

Figure 4. Modulus of Elasticity & Density of CRGPC30

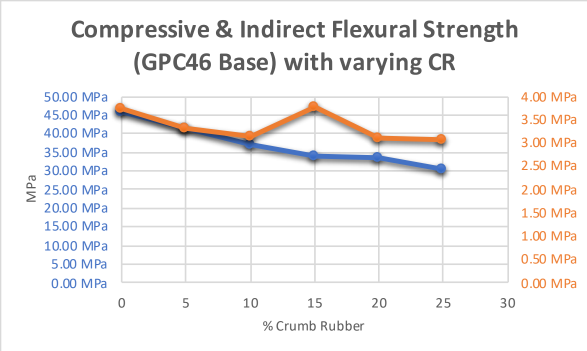

Figure 5. Compressive & Indirect Flexural Strength of CRGPC46

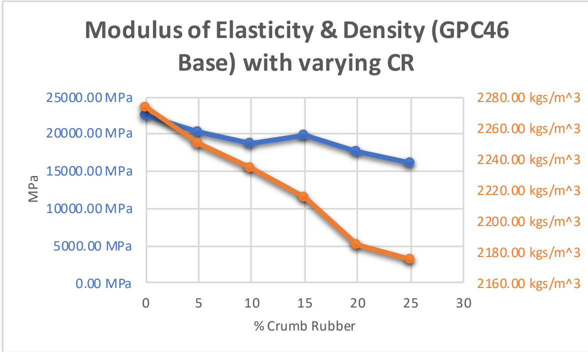

Figure 6. Modulus of Elasticity & Density of CRGPC46

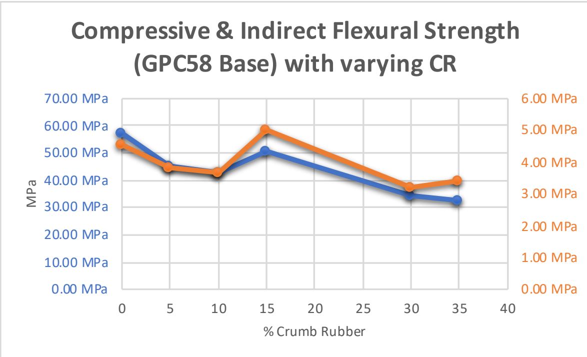

Figure 8. Compressive & Indirect Flexural Strength of CRGPC58

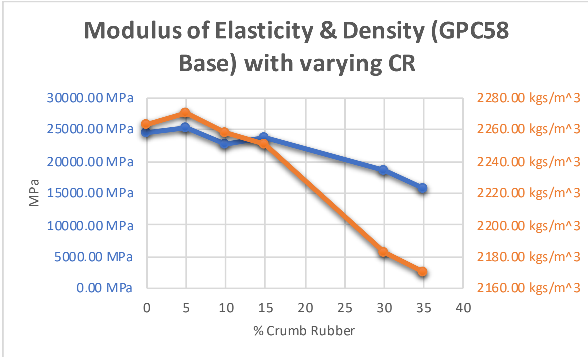

Figure 7. Modulus of Elasticity & Density of CRGPC58

Comparison of Actual to Predicted Modulus of Elasticity (MPa)

Table 5. Comparison of Actual to Predicted Modulus of Elasticity (MPa)

Mix	Actual	(ACI Committee 318-08, 2008)	(ACI Committee 318-11, 2011)	(AS 3600, 2009)
GPC30	15886.75	24484.65	19307.85	25158.71
GP5GPC30	14088.35	22766.94	17525.82	22836.67
CR10GPC30	13801.26	22681.83	17270.16	22503.54
CR15GPC30	12829.36	21660.59	16148.93	21042.55
GPC46	22524.91	30351.65	24262.19	31614.36
CR5GPC46	20238.84	28833.80	22701.95	29581.32
CR10GPC46	18801.69	27211.87	21204.04	27629.51
CR15GPC46	19777.47	26104.85	20076.25	26159.96
CR20GPC46	17705.88	25900.95	19510.81	25423.18
CR25GPC46	16104.79	24697.55	18481.15	24081.50
GPC58	24634.41	33915.25	26937.44	35100.30
CR5GPC58	25250.64	30096.79	24019.30	31297.87
CR10GPC58	22646.33	29289.33	23183.72	30209.09
CR15GPC58	23793.22	31881.96	25112.63	32722.52
CR30GPC58	18495.55	26154.62	19680.12	25643.79
CR35GPC58	15733.63	25599.22	19094.22	24880.34

Note: Red figures indicate that the actual value falls outside of the predicted value by ± 20%.

Graphical Representation of Actual to Predicted Modulus of Elasticity (MPa)

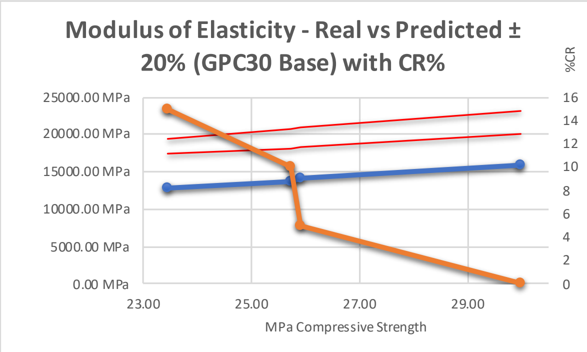

Figure 10. GPC30 Modulus of Elasticity - Real vs Predicted ± 20%

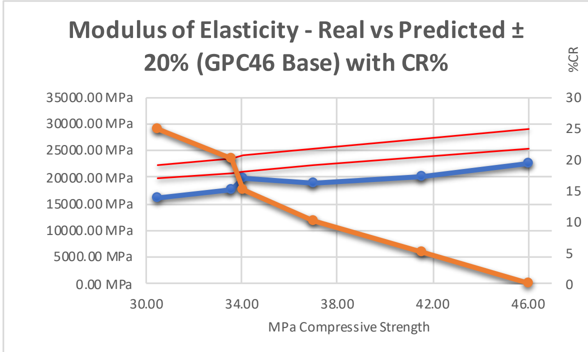

Figure 9. GPC46 Modulus of Elasticity - Real vs Predicted ± 20%

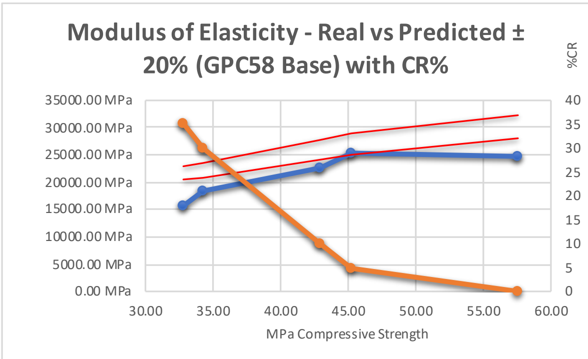

Figure 11. GPC58 Modulus of Elasticity - Real vs Predicted ± 20%

Note: Red lines represent the upper and lower boundaries as a combination of the individual ± 20% limits of the modulus of elasticity prediction for the Standards. To meet all Standards the Blue (Actual) line must fall within the Red boundary limits.

Characteristic Properties of similar Strength CRGPC

Due to time constraints the production of three different mixes with similar compressive strengths was not achieved. However, in the process of obtaining the core 5, 10 and 15% data and attempting to obtain the desired compressive strength mixes there were three sets of two different mixes that had similar compressive strengths that can be compared. These included the follow with the stipulated comparable compressive strength:

Comp 1	*CR10GPC58 – CR5GPC46*	*43MPa*
Comp 2	*CR30GPC58 – CR15GPC46*	*34MPa*
Comp 3	*CR35GPC58 – CR20GPC46*	*32MPa*

Table 6. Characteristic Properties of similar Strength CRGPC

Mix	Compressive Strength	Modulus of Elasticity (MPa)	Density (kg/m^3)	E_c Difference	Density Difference
CR10GPC58	41.55	20238.84	2249.90	2407.49 MPa	8.00 kg/m^3
CR5GPC46	42.88	22646.33	2257.91	11.90%	0.36%
CR30GPC58	34.19	18495.55	2182.95	1281.92 MPa	32.01 kg/m^3
CR15GPC46	34.06	19777.47	2214.95	6.93%	1.47%
CR35GPC58	32.75	15733.63	2170.24	1972.25 MPa	1432 kg/m^3
CR20GPC46	33.53	17705.88	2184.56	12.54%	0.66%

V. Discussion

It was difficult to establish the three core GPC mixes to use for this experiment. Developing and creating GPC mixes is a learning process that is taking a considerable amount of time to understand. Even with the restriction of variables, there are many elements of mix design that can be varied with each of them yielding different results. Although using previous mix designs as a basis for core mixes many modifications have had to be made in order to yield the desired compressive strengths. This is primarily attributed to the initial inconsistencies within the chemical composition of the AAFA being used for this experimental research.

Pretreatment of crumb rubber has been carried out in order to remove the smooth surface and improve adherence and mechanical resistance with in the CR GPC paste bond. Results from the pretreatment of the crumb rubber have been documented and photographed. This has been done to verify the recommendations given from various sources as referenced in section 2.3.2 of this document. *Figures 1* and *2* Gives visual representation of the effect's sodium hydroxide has as a pretreatment solution for crumb rubber. *Figures 1* and *2* Clearly demonstrate the crumb rubber's roughened surface caused from the 24-hour NaOH pre-treatment process. Additional images of the pre-treated CR can be found in *Appendix N*.

The crumb rubber pre-treatment procedure was altered after producing the GPC58 Core, 5 and 10% mixes. Inspections of the pre-treated crumb rubber revealed that a portion of the crumb rubber was being left untreated due to the cut plastic container lid failing to keep the crumb rubber submerged in the Sodium Hydroxide throughout the 24-hour period. Subsequently, a stainless-steel crumb rubber retention gauze was produced, adopted and maintained for the remainder of the GPC mixes. Inspections verified that the stainless-steel gauze was allowing the crumb rubber to be pretreated adequately.

Results for testing of the Core, 5, 10 and 15% CRGPC mixes had several points for concern. The GPC58 mixes were the first samples to be developed which highlighted some potential issues with the intended production plan. GPC58 mixes were produced one at a time ie GPC58 day 1, CR5GPC58 Day 2, …etc. This had the possibility for inducing human error within measurements as the option for weighing all the mix components at once and verifying quantities with a visual inspection was missed. CR15GPC58 yielded a 5MPa higher compressive strength than the CR5GPC58, which indicates a potential error in the either the crumb rubber pre-treatment or GPC mixing process. As such, the results from the CR15GPC58 have been deemed an outlier and excluded from both the Standards predicted modulus and similar compressive strength analysis.

The GPC58 and GPC46 mixes indicated an almost identical and linear rate of compressive strength decline with increasing crumb rubber content. This gave a compressive strength reduction coefficient of approximately 0.6. Whilst the GPC30 results yielded a compressive strength reduction coefficient of approximately 0.4.

$$C_{CR} = C_0 - (R_c \times CR\%)$$

Where: $C_{CR} = Compressive\ strength\ with\ x\%\ crumb\ rubber$
$C_0 = Initial\ compressive\ strength\ with\ 0\%\ crumb\ rubber\ (core\ mix)$
$CR = \%\ of\ crumb\ rubber\ added\ as\ volumetric\ replacement\ of\ fine\ aggregate$
$R_c = Compressive\ strength\ reduction\ Coefficient$

This indicates that the compressive strength reduction, due to the addition of crumb rubber as a percentage volumetric replacement of fine aggregate, is highly dependent on the initial core mix compressive strength. In order to develop a more comprehensive equation to predict the compressive strength reduction further testing is required. The increase in crumb rubber content has not altered the inherent relationship between the compressive strength and the Indirect flexural strength (C_{flex}) with the C_{Flex} remaining between 8-10% of the C_{cr} throughout the testing series.

The E_c exhibits very similar E_c reduction coefficient (R_m), relative to the initial E_c value, as the R_c. The R_m rates are as follows:

$$R_m(GPC30) = 189.19, with\ E_{c0} = 15886.75MPa$$
$$R_m(GPC46) = 221.28, with\ E_{c0} = 22524.91MPa$$
$$R_m(GPC58) = 259.51, with\ E_{c0} = 24634.41MPa$$

From these results it is easier to observe a trend between the initial E_c and the E_c reduction coefficient. It can be seen that the relationship is as follows:

$$R_m = \frac{E_{c0}}{100} \qquad \text{therefore} \qquad R_c \approx \frac{E_{c0}}{50000}$$

Tables 5 and *Table 10 (Appendix J)* demonstrate comparisons between the tested specimen characteristic properties and that of the predictive characteristic property equations from various Standards. As expected the variance between the indirect tensile strength and the predicted tensile strength has a less than a 20% variance. This verifies that CRGPC maintains the universal concrete relationship of tensile strength being approximately 8-10% of its compressive strength. However, variance in the tested to the predicted E_c highlights a greater than 20% variance. This can be attributed to the CR properties increasing the E_c rate of decline as discussed in the comparative strength sample analysis. This indicates that current OPC and GPC standards are insufficient and independent equations need to be developed for predicting the E_c of CRGPC.

After production and testing of the Core, 5, 10 and 15% mixes the next objective was to identify potential tends within the compressive strength of the samples relative to the CR content. Using a combination of linear and polynomial predictive traces it was determined that to achieve additional samples with comparable compressive strengths that both the GPC46 and GPC58 would have additions of crumb rubber at 20, 25% and 30, 35% respectively. Final results yielded three different similar compressive strength ranges with two specimens for each range to compare. First step in the analysis was to determine whether the densities for the pairs of specimens where close enough to ensure that any difference in the E_c could be attributed to the addition of the crumb rubber and not the inherent tendency for the E_c to reduce with density. The comparable samples seen in *Table 6* exhibit very similar densities with the maximum difference seen between the 34MPa comparable samples at only 1.47% (32km/m^3). When looking at the comparable samples there is a clear identifiable and distinguishable difference in there E_c. The E_c between the couples is significantly smaller in the sample that has the most additions of crumb rubber. As the densities are very similar this can only be attributed to the additions of the crumb rubber to the geopolymer concrete mix. The difference in the E_c differ between the quantity of crumb rubber added and the difference between the amount added in each sample. The 42MPa samples have only 5% difference in crumb rubber additions and exhibits the largest difference in E_c at 2407.49MPa. However, the total crumb rubber percentages added is quite low (between 5-10%) and the E_c's are higher making the percentage difference 11.90%. The 34MPa samples exhibited the lowest difference in E_c at only 1282.92MPa with a range of 15-30%. The 32MPa samples had the same difference in crumb rubber content but at a higher rate of addition (20-35%). This returned a difference in the E_c of 1972.25MPa and the highest difference as a percentage at 12.54% due to the lower E_c. Although these results returned an identifiable and important difference in there E_c it is difficult to identify a trend with limited data obtained from the testing performed.

It has been proven that there is a relationship between the E_c and compressive strength (f'_c) for OPC and E_c, f'_c and density for GPC. This can be observed through any of the Standards E_c prediction equations. The difficulty with crumb rubber geopolymer concrete is that the CR causes a decrease in the compressive strength and the material density consequently resulting in a reduction in the E_c. This makes it difficult to determine if the reduction in E_c is due to the energy absorption properties of the included CR or the inherent change due to the compressive strength and density reduction. Concretes of the same compressive strength and density theoretically have the same E_c. Analysing comparable compressive strength and density CRGPC mixes with different quantities of CR is intended to establish if the energy absorbing properties of the CR cause a reduction in the E_c independent of the other E_c dependent factors (Compressive strength and density).

A slight modification to the AS3600 E_c predictive equation would return a value that has all of the samples return a predicted value that has an error factor of < 19% for the testing series:

Option 1 $E_{cr} = (0.026 \times \rho^{1.5}) \times C_{cr}{}^{0.53}$ *Accuracy - max (19.01%), Average (6.59%)*

Option 2 $E_{cr} = (0.026 \times \rho^{1.52}) \times C_{cr}{}^{0.5}$ *Accuracy - max (14.32%), Average (6.72%)*

These equation accuracies are valid for this testing series only and additional testing and analysis of these equations with other GPC and CRGPC samples needs to be carried out to validate either Option 1 or 2 equations.

Implementing Option 2 and the E_c reduction coefficient postulate could lead to predicting the compressive strength of a CRGPC given an initial Core GPC mix compressive strength (C_0).

$$C_{CR} = C_0 - \left[\frac{(0.026 \times \rho_0{}^{1.52}) \times C_0{}^{0.5}}{50000} \times CR\%\right]^{1.14}$$ *Average 6.84% accuracy*

Where: $C_{CR} = Compressive\ strength\ with\ x\%\ crumb\ rubber$
$C_0 = Initial\ compressive\ strength\ with\ 0\%\ crumb\ rubber\ (core\ mix)$
$CR = \%\ of\ crumb\ rubber\ added\ as\ volumetric\ replacement\ of\ fine\ aggregate$
$\rho_0 = Density\ of\ core\ mix$

This equation and its accuracy are valid for this testing series only and additional testing and analysis of this equations with other GPC and CRGPC samples needs to be carried out to validate its applicability to CRGPC.

Another approach to Analysing the empirical to analytical E_c is raised when observing *Figures 9, 10* and *11*. In these figures it is highlighted that empirical E_c follows that same response path as the analytical values independent of the qty of CR additions. Although we observed a lower E_c with higher CR content in *Table 6*, these values are still close relative to the ± 20% limitations of the applicable standards. Taking the AS3600, 2009 (*Equation 5*), ACI Committee 318-11 (*Equation 4*) and applying a fixed reduction factor a more accurate analytical comparison is observed.

Option 3 $E_{cr} = 0.043\rho^{1.5} f'_c{}^{0.5} - 8344\ (MPa)$ *Accuracy - max (9.94%), Average (4.63%)*

Option 4 $E_{cr} = 33\rho^{1.5} f'_c{}^{0.5} - 2012000\ (KPa)$ *Accuracy - max (12.85%), Average (5.86%)*

When applied to this test series the AS and ASI equations yield the maximum and average figures above, this is well within the requirement of ± 20%. *Appendix J, figures 14* and *15* demonstrate the effectiveness of the proposed amendments to the existing standards. This constant correction factor could attribute changes in E_c to density values, effected by the fitness of the Fly Ash used in these experiments. This would indicate that standardised equations may not be appropriate for application with CRGPC or GPC due gross source material differences and their unpredictable effects.

VI. Conclusion

The research conducted on the effects of substituting traditional sand fines aggregates with crumb rubber aggregates derived from end of life tyres tires demonstrated a decrease in the characteristic properties of the tested design geopolymer concrete mixes. The reduction is seen to be proportional to the rate of crumb rubber additions however is non-linear and difficult to trace. The comparison of the crumb rubber geopolymer concrete samples with the existing ASI and Australian Standards, for predicting the E_c based on the concrete's compressive strength, demonstrated unsuitability for application in crumb rubber geopolymer concrete. However, the indirect tensile strength predictive equations remain applicable. Standardised equations for predicting E_c may not be appropriate for application with CRGPC or GPC unless source material consistency can be verified. Evaluation of similar strength geopolymer concrete with different percentage additions of crumb rubber identified that there is a different in their E_c despite having comparable sample densities. However, the CRGPC still yields strengths that suit an abundance of purposes and offers significant environmental and economic benefits. Additionally, the decrease in E_c could be extremely beneficial for use in applications such as sound barriers, crash barriers, seismic exposed structures or any application that requires higher energy absorption or deflection characteristics.

VII. Recommendations

It is recommended that continuation of experimental research be carried out in order to further establish trends in the changes to the characteristic properties of CRGPC. This is in order to institute a standard for prediction of E_c and tensile strength base on a CRGPC's compressive strength enabling easier and encouraged solicitation of CRGPC.

Acknowledgements

I would like to express my sincerest gratitude to several individuals and organisations for their undying support, guidance, advice and constructive feedback throughout the course of this project.

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Appendices

Appendix A – Fly Ash Data Sheet

STANDARD FLY ASH CERTIFICATE

FINAL

Prior Reports: None

Certificate Number: CERT171187

Issued: 14 September 2017

Flyash Australia Pty Ltd
ABN 68 002 840 271
Head Office
C/- Lindfield Corporate Centre
Suite 18, 12 Tryon Road
Lindfield NSW 2070
Tel : (02) 9413 8422
Fax: (02) 9413 84.32
www.flyashaustralia.com.au

Product being certified: Eraring Monthly Grab Fly Ash
Product sample date: 06-Aug-2017
Sample Identification: Sample Code: 17080308
Source Power Station: Eraring Power Station
Sample Condition: Tested as Received. Testing Commenced on 09-Aug-2017
Certifying Laboratory: Cement Australia - Darra Laboratory,
18 Station Avenue, Darra Queensland 4076 Australia.

Test Results

Test	Moisture %	Fineness @ 45 micron % Passed	Loss on Ignition %	Sulfuric Anhydride %	Available Alkali %	Chloride Ion %	Chemical Composition %
Result	< 0.1	90	1.8	0.1	Not Tested	0.005	93.1
Test Method	AS3583.2	AS3583.1	AS3583.3	AS2350.2	AS3583.12	AS3583.13	AS2350.2
AS 3582.1	0.5% Maximum	75% Minimum	4.0 % Maximum	3.0% Maximum	-	0.1 % Maximum	70% Minimum

Test	Relative Density	Relative Water Requirement %	Strength Index %
Result	2.13	96	93
Test Method	AS3583.5	AS3583.6	AS3583.6
AS 3582.1	-	-	75% Minimum

Reference Cement Details	
Identification::	17080317
Source:	Goliath GP
Product Type:	Type GP
Sample Date:	09-Aug-17

Additional Testing - Oxides

Test	CaO by XRF %	SiO_2 by XRF %	Al_2O_3 by XRF %	Fe_2O_3 by XRF %	SO_3 by XRF %	MgO by XRF %	Na_2O by XRF %
Result	1.6	65.5	24.5	3.1	0.1	0.5	0.45
Test Method	AS2350.2	AS2350.2	AS2350.2	AS2350.2	AS2350.2	AS2350.2	AS2350.2

Test	K_2O by XRF %	SrO by XRF %	TiO2 by XRF %	P_2O_5 by XRF %	Mn_2O_3 by XRF %	Total Alkali %
Result	1.43	<0.1	1.0	0.3	< 0.1	1.39
Test Method	AS2350.2	AS2350.2	AS2350.2	AS2350.2	AS2350.2	AS2350.2

This sample grade conforms to the following requirements of AS 3582.1:2016

Special	Grade 1	Grade 2
	X	

Approved Signatory

A Prem
Signatory - Cement Australia
Chemical Testing
Construction Materials Testing

Accredited for compliance with ISO/IEC 17025 - Testing. The results of the tests, calibrations and/or measurements included in this document are traceable to Australian/national standards.

Cement Australia - Darra Laboratory
NATA Accredited Laboratory Numbers
187 188

NATA
ACCREDITED FOR **TECHNICAL COMPETENCE**

Notes:

1 7 0 8 0 3 0 8

C E R T 1 7 1 1 8 7

Darra Laboratory Document: DA-SF-019a

Page 1 of 1

Appendix B – 7mm BM Material Test Report

BORAL

Mugga Laboratory
Boral Resources (Country) Limited
ACN. 000 187 002
Mugga Lane, Woden 2603
PO Box 3229
MANUKA ACT 2603

Telephone: (02) 6239 5064
Facsimile: (02) 6239 5065

Material Test Report

Report No: MAT:WMU-11/00431-Q01

Client: BORAL COUNTRY

Project: QUALITY CONTROL

This Test Report is not Endorsed by NATA

Sample Details

Sample ID:	WMU-11/00431-Q01
Date Sampled:	28/02/2011
Source:	Mugga Quarry
Material:	Mugga 7mm BM
Stockpile:	N/A
Lot No:	N/A
Progressive Tonnes:	N/A
Total Tonnes:	N/A
Sampling Method:	AS1141.3.1 Clause 6.9.5a
Specification:	MQ07

Other Test Results

Description	Method	Result	Limits

Particle Size Distribution

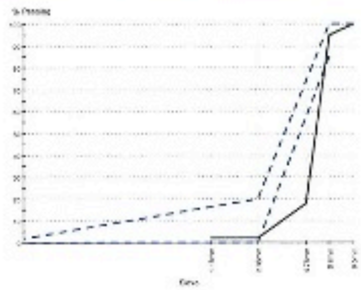
Method: Grading and Finer 75µm [AS 1141.11.1/12]

Drying by: Oven

Note: Sample Washed

Sieve Size	% Passing	Limits
9.5mm	100	–100
6.7mm	95	85 – 100
4.75mm	18	
2.36mm	2	0 – 20
1.18mm	2	
Finer 75µm	1	0 – 2

Chart



Comments
N/A

Form No: 18909.V1.00, Report No: MAT:WMU-11/00431-Q01 (c) 2000-2005 QESTLab by SpectraQEST.com Page 1 of 1

Appendix C – 10mm BM Material Test Report

BORAL® Build something great™

Canberra Laboratory
Boral Resources (Country) Limited
ACN. 000 187 002
Mugga Lane, Woden 2603
PO Box 3229
MANUKA ACT 2603

Telephone: (02) 6239 5064
Facsimile: (02) 6239 5065

Material Test Report

Report No: MAT:WMU-16/00732-Q01
Issue No: 1
This report replaces all previous issues of report no 'MAT:WMU-16/00732-Q01'

Client: MUGGA 1 QUARRY
MUGGA 1 QUARRY, MATERIAL PURCHASES C/-
GREYSTANES NSW 2145

Project: QUALITY ASSURANCE

Accredited for compliance with ISO/IEC 17025

NATA ACCREDITED FOR TECHNICAL COMPETENCE

NATA Accredited Laboratory Number: 3128

Approved Signatory: Mauro Aviles (LAB TECHNICIAN - AGG)
Date of Issue: 22/04/2016

THIS DOCUMENT SHALL NOT BE REPRODUCED EXCEPT IN FULL

Sample Details

Sample ID:	WMU-16/00732-Q01
Date Sampled:	21/04/2016
Source:	Mugga Quarry
Material:	Mugga 10mm BM
Stockpile:	60501
Lot No:	
Progressive Tonnes:	
Total Tonnes:	
Sampling Method:	AS1141.3.1 Clause 9.4
Specification:	MQ10

Other Test Results

Description	Method	Result	Limits
Grading [AS 1141.11.1]			
Fineness Modulus		6.0	
Curvature Coefficient		1.12	
Uniformity Coefficient		1.56	
Average Least Dimension [AS 1141.20.1]			
Average Least Dimension (mm)		5.4	

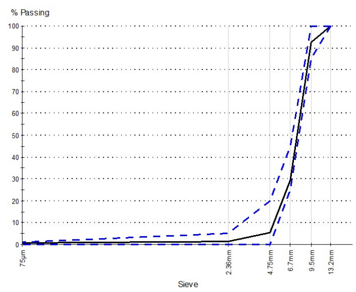
Particle Size Distribution

Method: Grading [AS 1141.11.1]
Drying by: Oven

Note: Sample Washed

Sieve Size	% Passing	Limits
13.2mm	100	100
9.5mm	92	85 – 100
6.7mm	29	25 – 45
4.75mm	5	0 – 20
2.36mm	1	0 – 5
75µm	1	0 – 1

Chart



Comments

N/A

Form No: 18909, Report No: MAT:WMU-16/00732-Q01

Page 1 of 1

Appendix D – 14mm BM Material Test Report

Australian Construction Materials BORAL

MATERIALS TECHNICAL SERVICES
BORAL RESOURCES (NSW) PTY LTD
ABN 51 000 755 307
Unit 4, 3-5 Gibbon Road
Baulkham Hills NSW 2153 Australia
PO Box 400, Winston Hills NSW 2153
Telephone 61 2 9624 9900
Facsimile 61 2 9624 9999

TEST REPORT
CLIENT: Boral Country - ACT
PROJECT: Quality Control – 3 monthly testing for December 2010 FILE NO: 19/10
SOURCE: Mugga Quarry
TEST METHOD: AS1141 – Methods for Sampling and Testing Aggregates
SPECIFICATION: RTA 3152 and Boral Asphalt ITP

Client Sample No:			8586
Sample Description:			14mm Agg.
Laboratory Sample No:			111135
Date Sampled:			6.12.10
Test Method	**Test**	**Spec.**	**Results**
AS1141.11.1*	% Passing A.S.Sieve		
	19.0mm	100	100
	13.2mm	85-95	95
	9.5mm	10-25	26
	6.7mm	0-10	6
	4.75mm	0-5	5
	2.36mm	-	4
	1.18mm	-	3
AS1141.12	Material finer than 75 micron (%)	0-1	2
AS1141.14	Mis-shapen particles (%)		
	Ratio 2:1	Max. 25	10
	Ratio 3:1	Max. 10	1
AS1141.6.1	Particle Density (Dry) (t/m³)		2.63
	Particle Density (SSD) (t/m³)		2.66
	Apparent Particle Density (t/m³)		2.71
	Water Absorption (%)	Max. 2.5	1.1
AS1141.22	Ave. Dry Strength (kN)		260
	Ave. Wet Strength (kN)	Min. 150	170
	Wet/Dry Strength Variation (%)	Max. 35	35
	Test Fraction (mm)		-13.2+9.5
	The amount of significant breakdown (%)		<0.2
	The size of the test cylinder = 150mm diam.		

*Sample washed over 75 micron sieve as per AS1141.11.1 Clause 5.6.
Sample submitted by client.

C. Bounassif, J. Barkley, J. Adams, T. Allen, M. Dawes, P. Hannah, L. Turnbull, R. Crabb, D. Taylor, M. Hawkins, QC File, File, Ref: 5677.lnt

NATA ACCREDITED FOR TECHNICAL COMPETENCE

Approved Signatory Richard Bawer

Date 24.12.10 Serial No. 92256

This document is issued in accordance with NATA's accreditation requirements.
Accredited for compliance with ISO/IEC 17025

NATA Accredited Laboratory
Number: 547

Appendix E – Sodium Silicate D Grade

PRODUCT SPECIFICATION

IMCD

Division :	Phone :
Food	1300 655328
Filtration	1300 655328
Performance Products	1300 658663
Plastics & Rubber	1300 130295
Surface Coatings & Petrochemicals	1300 130295

IMCD Australia Limited

PO Box 689
1st Floor, 372 Wellington Road
Mulgrave VIC 3170, Australia
Phone: +61 (03) 8544 3100
Fax: +61 (03) 85443299
Email:
www.imcdgroup.com

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SODIUM SILICATE D GRADE

Product Code: 4018401 / 4201613 / 4910112
Supplier No: 0000882

Product: D

Description: A 2.00 ratio liquid sodium silicate of 1.52 *g/cc* density

Properties:	**Specification**
Na_2O%.wt	14.5 - 14.9
SiO_2 %.wt	29.1 - 29.7
Solids%.wt	43.6 - 44.6
Ratio *(SiO_2 %/Na_2O%)*	1.95 - 2.05
Density, g/cc @ 20 ° C	1.50 - 1.53
Viscosity, cps @ 20 ° C	250 - 450

Document R5a – Updated: April 2007

Appendix F – Mix Design GPC32

Characteristic Strength (fck)	30 MPa
Heat	60.00 kg/m^3
Duration	24 hr
S Value	6

Fly Ash % Passed 45 micron	90%	Over 45 micron is inert
Fly Ash Density	2130.00 kg/m^3	
Fly Ash Specific Surface	412 m^2/kg	Blaine approx
ROS 45 %	10%	422.54 m^2/kg ??

Fine Aggregate	Sand
Fineness Modulus	2.5
Water Absorption	
SSD Density	

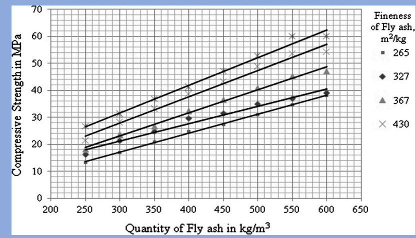
Course Aggregate	Crushed Granite
Size	10 mm
Minimum	5.4 mm
Maximum	13.4 mm
Water Absorption	
SSD Density	
Fineness Modulus	6
Co-efficient Curavture	1.12
Uniformity Co-efficient	1.56

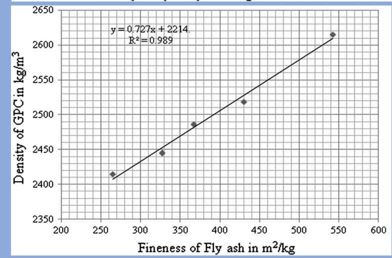
Alkaline Solution	Na2SiO3 + NaOH
Workability	Very High
Sodium Hydroxide Mol	16M
Sodium Silicate Conc	1.52 g/cc
Sodium Silicate Ratio	2
Solution to Fly Ash Ratio	0.5
Sodium Silicate - Sodium Hydroxide Ratio	2.5
Water - Fly Ash Ratio	0.35

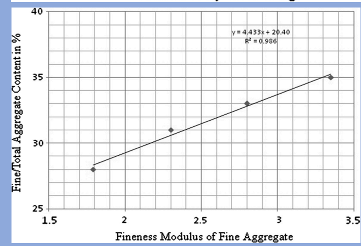
Geopolymer Concrete Mix			mass Solid	mass Water
Characteristic Strength (fck)	30 MPa			
Target Strength (Fck)	39.9 MPa			
Qty Fly Ash	445.76 kg/m^3			
mass of solution	222.88 kg/m^3			
mass of Na_2SiO_3	159.20 kg/m^3	→	70.21 kg/m^3	88.99 kg/m^3
mass of NaOH	63.68 kg/m^3	→	28.27 kg/m^3	35.41 kg/m^3
Water Content	185.00 kg/m^3			124.40 kg/m^3
Adjust Water Content	60.60 kg/m^3			
Wet density of GPC	2513.52 kg/m^3			
Fine/Total aggregate	31.48%			
Total Aggregate	1784.28 kg/m^3			
Fine Aggregate	561.74 kg/m^3			
Coarse Aggregate	1222.54 kg/m^3			

Summary

Reference Tables







Grade	Quantity of water (kg/m³) (W/GPB)[a]	GPB (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)
M20	118.20	378	727.40	1350.88
	0.313	1	1.92	3.57
M25	118.20	445.50	707.53	1313.97
	0.265	1	1.59	2.95
M30	108.35	513	690.54	1282.43
	0.211	1	1.35	2.5
M35	108.35	594	667.19	1239.07
	0.182	1	1.12	2.08
M40	98.50	661.50	649.37	1205.97
	0.149	1	0.98	1.82

Appendix G – Grade F Fly Ash Data Sheet

CLASS F FLY ASH

Composition

Class F fly ash is designated in ASTM C 618 and originates from anthracite and bituminous coals. It consists mainly of alumina and silica and has a higher LOI than Class C fly ash. Class F fly ash also has a lower calcium content than Class C fly ash. Additional chemical requirements are listed in Table 2.

Table 2. Class F fly ash Chemical Composition

Property	ASTM C618 Requirements, %
SiO_2 plus Al_2O_3 plus Fe_2O_3, min	70
SO_3, max	5
Moisture content, max	3
Loss on Ignition, max	6

Replacement

When used in portland cement, Class F fly ash can be used as a portland cement replacement ranging from 20-30% of the mass of cementitious material.

Advantages

When used as a portland cement replacement, Class F fly ash offers the following advantages when compared to unmodified portland cement:

- Increased late compressive strengths (after 28 days)
- Increased resistance to alkali silica reaction (ASR)
- Increased resistance to sulfate attack
- Less heat generation during hydration
- Increased pore refinement
- Decreased permeability
- Decreased water demand
- Increased workability
- Decreased cost ($80/ton for portland cement vs. $30/ton for fly ash).

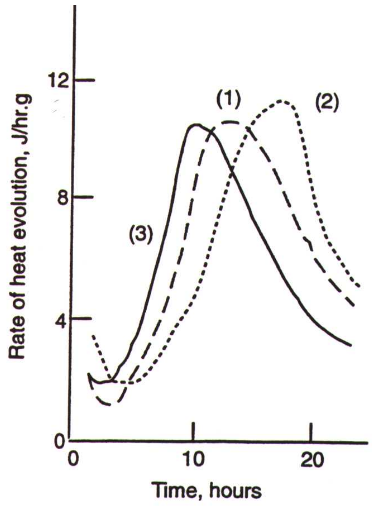


Figure 3.2.6. Heat evolution curves of the hydration at 20°C of ordinary Portland cement containing (1) 40% ordinary fly ash, (2) 40% high calcium fly ash, and (3) no fly ash (adapted from Uchikawa, 1986).

Cautions

When using Class F fly ash as a portland cement replacement, it is important to know several precautions. The time of set may be slightly delayed, and the early compressive strengths (before 28 days) may be decreased slightly. Also, the fine aggregate fraction of the concrete will need to be modified because fly ash has a lower bulk specific gravity than does portland cement, and therefore occupies a greater volume for an equal mass. If using any organic admixtures such as air entrainment, the amount added must be modified since the carbon (LOI) in the fly ash adsorbs organic compounds. Finally, if the fly ash has a high calcium content, it should not be used in hydraulic applications. When using this or any other alternative cementing material with portland cement, it is necessary to create trial mixtures to ensure proper proportioning for the desired properties.

References

CLASS C FLY ASH

Composition

Class C fly ash is designated in ASTM C 618 and originates from subbituminous and lignite coals. Its composition consists mainly of calcium, alumina, and silica with a lower loss on ignition (LOI) than Class F fly ash. Additional chemical properties are listed in Table 1.

Table 1. Class C fly ash Chemical Composition

Property	Requirements (ASTM C618), %
SiO_2 plus Al_2O_3 plus Fe_2O_3, min	50
SO_3, max	5
Moisture content, max	3
Loss on Ignition, max	6

Replacement

When used in portland cement, Class C fly ash can be used as a portland cement replacement ranging from 20-35% of the mass of cementitious material.

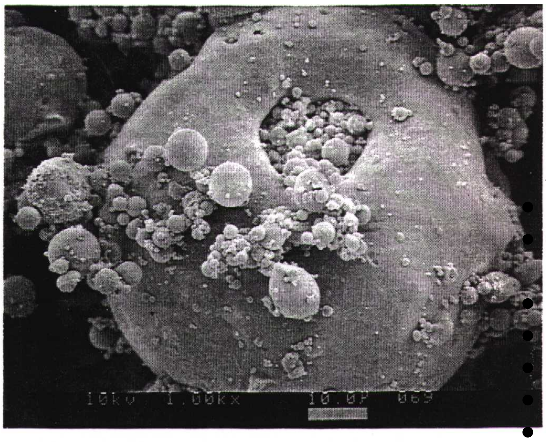


Figure 2.3.2. Fly ash showing large plerospheres containing smaller cenospheres (courtesy of Hills, 1995).

Advantages

When used as a portland cement replacement, Class C fly ash offers the following advantages when compared to unmodified portland cement:

- Increased early and late compressive strengths
- Increased resistance to alkali silica reaction (ASR) when >15% is added
- Less heat generation during hydration
- Increased pore refinement
- Decreased permeability
- Decreased water demand
- Increased workability
- Decreased cost ($80/ton for portland cement vs. $30/ton for fly ash).

Cautions

When using Class C fly ash as a portland cement replacement, it is important to know several precautions. The time of set may be slightly delayed. Also, the fine aggregate fraction of the concrete will need to be modified because fly ash has a lower bulk specific gravity than does portland cement and therefore occupies more volume for the same mass. Class C fly ash must replace at least 25% of the portland cement to mitigate the effects of alkali silica reaction. If using any organic admixtures such as air entrainment, the amount added must be modified since the carbon (LOI) in the fly ash adsorbs organic compounds. Finally, if the fly ash has a high calcium content, it should not be used in sulfate exposure applications. When using this or any other alternative cementing material with portland cement, it is necessary to create trial mixtures to ensure proper proportioning for the desired properties.

References

Appendix I – Fine Aggregate Particle Size Distribution

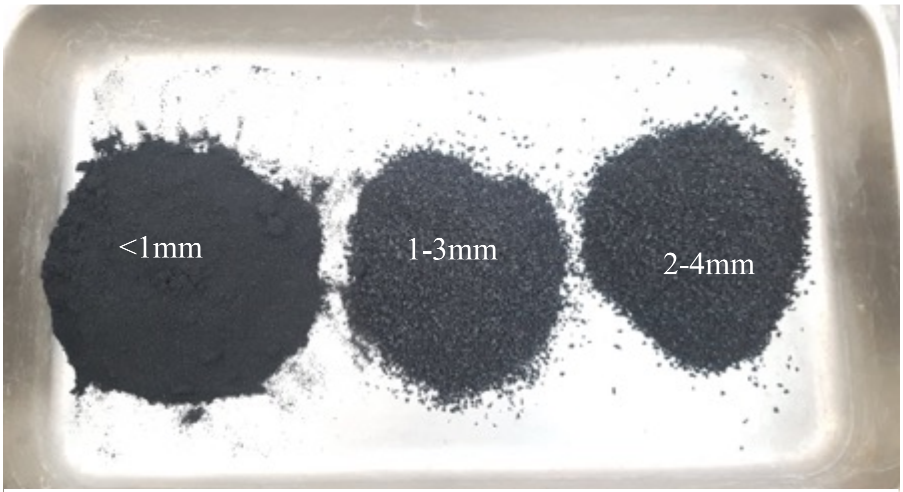


Figure I12. Crumb Rubber Particle Size.

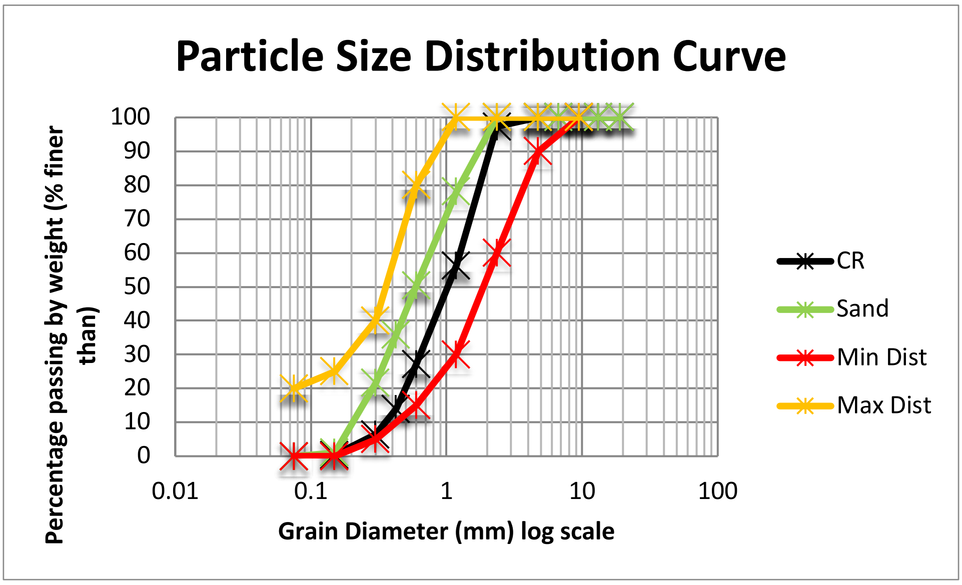


Figure I13. Particle Size Distribution Curve Sand, CR, Limits

Appendix J – Experimental Research Results

Table J7. Experimental Results Crumb Rubber 0%, 5%, 10%, 15%

Mix	Density (kg/m^3)	Compressive Strength (MPa)	Modulus of Elasticity (MPa)	Ind Tensile Strength (MPa)
GPC30	2252.25	29.96	15886.75	2.77
GPC46	2272.77	46.04	22524.91	3.75
GPC58	2263.07	57.49	24634.41	4.55
CR5GPC30	2216.35	25.91	14088.35	2.49
CR10GPC30	2200.23	25.71	13801.26	2.46
CR15GPC30	2169.56	23.45	12829.36	2.30
CR5GPC46	2249.90	41.55	20238.84	3.31
CR10GPC46	2234.41	37.01	18801.69	3.13
CR15GPC46	2214.95	34.06	19777.47	3.79
CR5GPC58	2270.30	45.27	25250.64	3.83
CR10GPC58	2257.91	42.88	22646.33	3.69
CR15GPC58	2250.55	50.80	23793.22	5.03

Table J8. Experimental Results CRGPC with similar compressive strengths

Mix	Density (kg/m^3)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Ind Tensile Strength (MPa)
CR5GPC30	2216.35	25.91	14088.35	2.49
CR20GPC46	2184.56	33.53	17705.88	3.10
CR25GPC46	2174.90	30.49	16104.79	3.07
CR30GPC58	2182.95	34.19	18495.55	3.21
CR35GPC58	2170.24	32.75	15733.63	3,41

Comparison of Actual to Predicted Indirect Flexural Strength (MPa)

Table 9. Comparison of Actual to Predicted Indirect Flexural Strength (MPa)

Mix	Actual	(ACI Committee 318-11, 2011)	(ACI Committee 363-92, 1992)
GPC30	2.77	3.04	3.23
GP5GPC30	2.49	2.83	3.00
CR10GPC30	2.46	2.82	2.99
CR15GPC30	2.30	2.69	2.86
GPC46	3.75	3.77	4.00
CR5GPC46	3.31	3.58	3.80
CR10GPC46	3.13	3.38	3.59
CR15GPC46	3.79	3.24	3.44
CR20GPC46	3.10	3.22	3.42
CR25GPC46	3.07	3.07	3.26
GPC58	4.55	4.22	4.47
CR5GPC58	3.83	3.74	3.97
CR10GPC58	3.69	3.64	3.86
CR15GPC58	5.03	3.96	4.21
CR30GPC58	3.21	3.25	3.45
CR35GPC58	3.41	3.18	3.38

Note: Red figures indicate that the actual value falls outside of the predicted value by ± 20%.

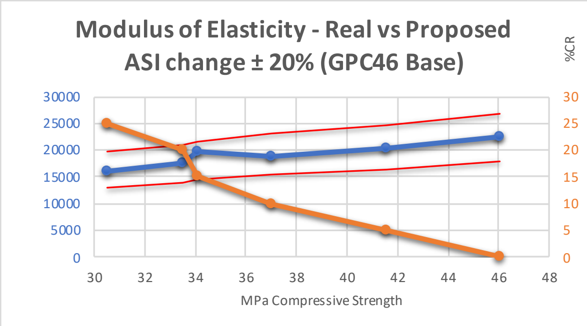


Figure 14. GPC46 E_c Real vs ASI with proposed change

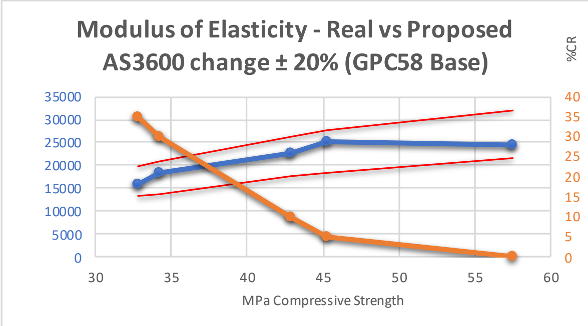
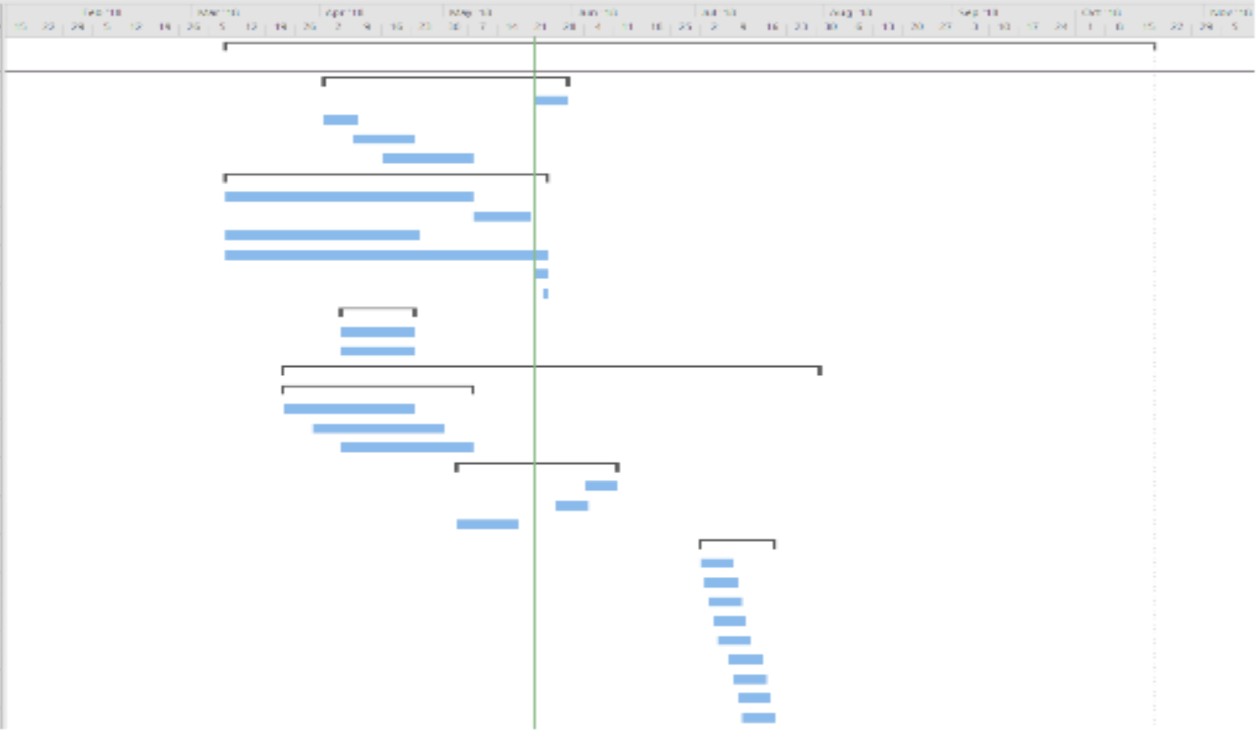


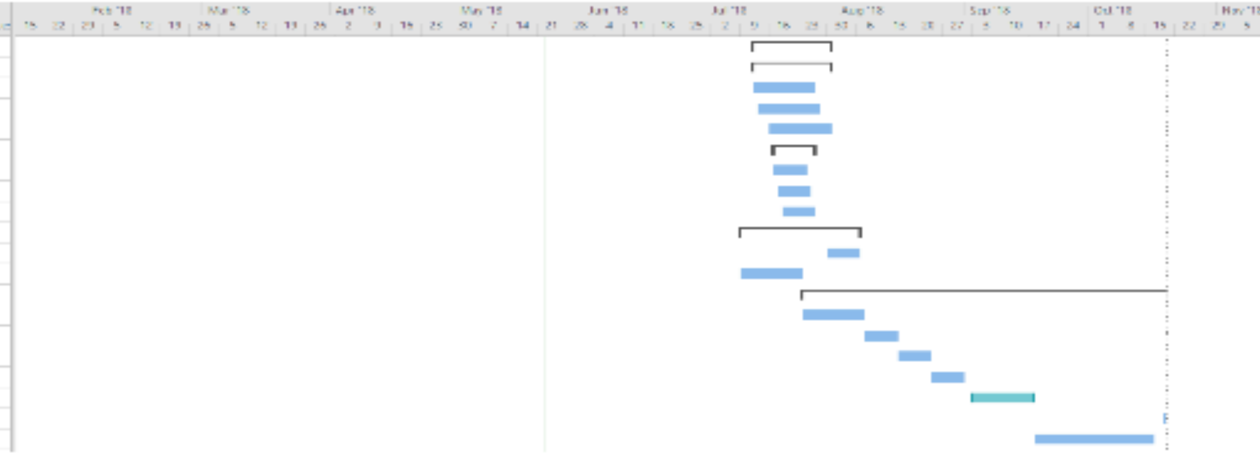
Figure 15. GPC58 E_c Real vs AS3600 with proposed change

Appendix K – Project Gantt Chart

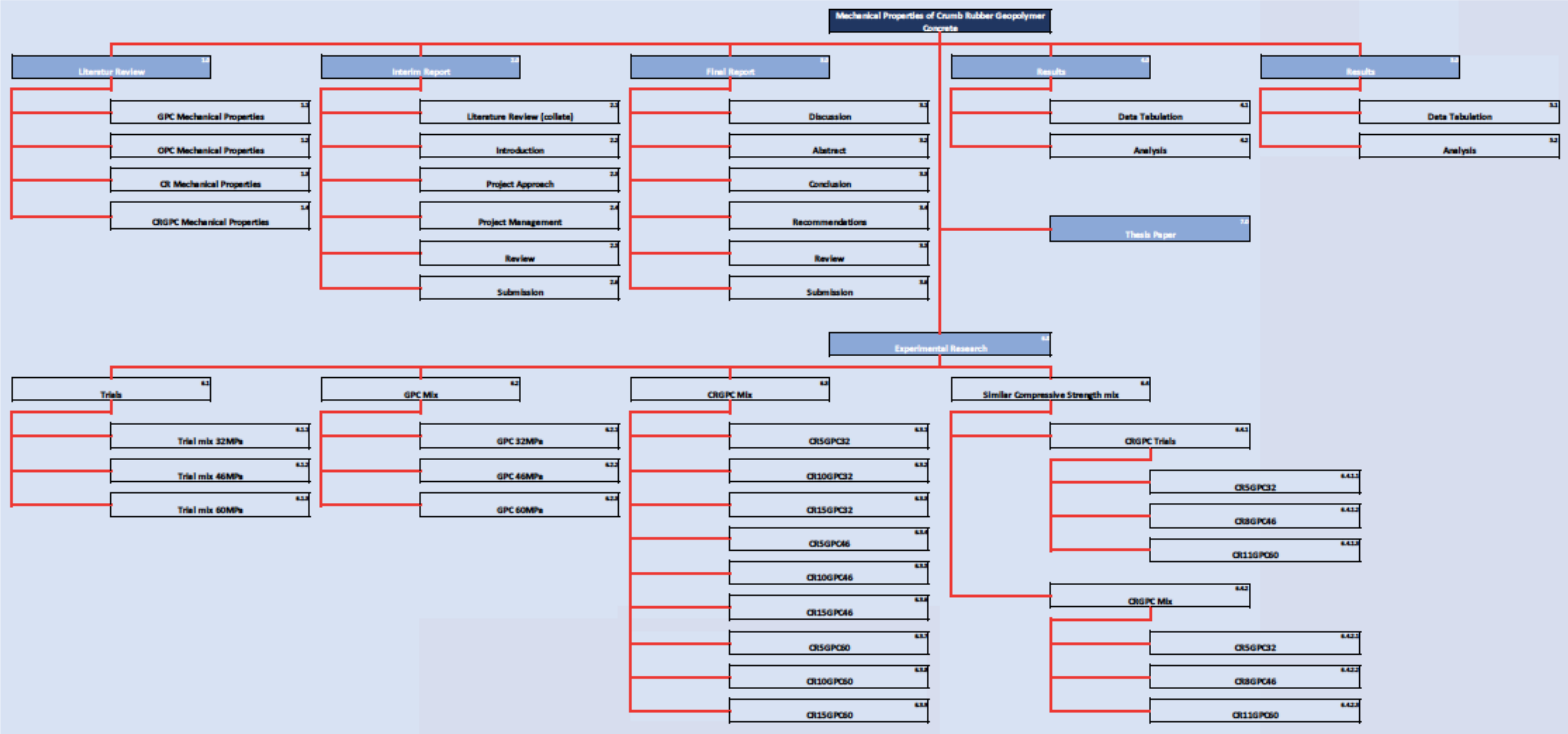
Task Name	Duration	Start	Finish	Predece
Mechanical Properties of Crumb Rubber Geopolymer Concrete	**161 days**	**Fri 9/03/18**	**Fri 19/10/18**	
Literature Review	**43 days**	**Mon 2/04/18**	**Wed 30/05/18**	
GPC Mechanical Properties	6 days	Wed 23/05/18	Wed 30/05/18	
OPC Mechanical Properties	6 days	Mon 2/04/18	Mon 9/04/18	
CR Mechanical Properties	11 days	Mon 9/04/18	Mon 23/04/18	
CRGPC Mechanical Properties	16 days	Mon 16/04/18	Mon 7/05/18	
Interim Report	**56 days**	**Fri 9/03/18**	**Fri 25/05/18**	
Literature Review	42 days	Fri 9/03/18	Mon 7/05/18	
Introduction	10 days	Tue 8/05/18	Mon 21/05/18	
Project Approach	33 days	Fri 9/03/18	Tue 24/04/18	
Project Management	56 days	Fri 9/03/18	Fri 25/05/18	
Review	3 days	Wed 23/05/18	Fri 25/05/18	
Submission	1 day	Fri 25/05/18	Fri 25/05/18	
Support	**12 days**	**Fri 6/04/18**	**Mon 23/04/18**	
TSG	12 days	Fri 6/04/18	Mon 23/04/18	
Consumables	12 days	Fri 6/04/18	Mon 23/04/18	
Experimental Research	**92 days**	**Fri 23/03/18**	**Mon 30/07/18**	
Trials	**32 days**	**Fri 23/03/18**	**Mon 7/05/18**	
Trial Mix 32MPa	22 days	Fri 23/03/18	Mon 23/04/18	
Trial Mix 46MPa	22 days	Fri 30/03/18	Mon 30/04/18	
Trial Mix 60MPa	22 days	Fri 6/04/18	Mon 7/05/18	
GPC Mix	**27 days**	**Fri 4/05/18**	**Mon 11/06/18**	
GPC 32MPa	6 days	Mon 4/06/18	Mon 11/06/18	
GPC 46MPa	6 days	Mon 28/05/18	Mon 4/06/18	
GPC60MPa	11 days	Fri 4/05/18	Fri 18/05/18	
CRGPC Mix	**14 days**	**Mon 2/07/18**	**Thu 19/07/18**	
CR5GPC32	6 days	Mon 2/07/18	Mon 9/07/18	
CR10GPC32	6 days	Tue 3/07/18	Tue 10/07/18	
CR15GPC32	6 days	Wed 4/07/18	Wed 11/07/18	
CR5GPC46	6 days	Thu 5/07/18	Thu 12/07/18	
CR10GPC46	6 days	Fri 6/07/18	Fri 13/07/18	
CR15GPC46	6 days	Mon 9/07/18	Mon 16/07/18	
CR5GPC60	6 days	Tue 10/07/18	Tue 17/07/18	
CR10GPC60	6 days	Wed 11/07/18	Wed 18/07/18	
CR15GPC60	6 days	Thu 12/07/18	Thu 19/07/18	



Task Name	Duration	Start	Finish	Predecessors
Similar Compressive Strength Mix	**13 days**	**Thu 12/07/18**	**Mon 30/07/18**	
CRGPC Trials	**13 days**	**Thu 12/07/18**	**Mon 30/07/18**	
CR5GPC32	11 days	Thu 12/07/18	Thu 26/07/18	
CR8GPC40	11 days	Fri 13/07/18	Fri 27/07/18	
CR11GPC50	11 days	Mon 16/07/18	Mon 30/07/18	
CRGPC Mix	**8 days**	**Tue 17/07/18**	**Thu 26/07/18**	
CR5GPC32	6 days	Tue 17/07/18	Tue 24/07/18	
CR8GPC40	6 days	Wed 18/07/18	Wed 25/07/18	
CR11GPC50	6 days	Thu 19/07/18	Thu 26/07/18	
Results	**21 days**	**Mon 9/07/18**	**Mon 6/08/18**	
Data Tabulation	6 days	Mon 30/07/18	Mon 6/08/18	
Analysis	11 days	Mon 9/07/18	Mon 23/07/18	
Final Report	**64 days**	**Tue 24/07/18**	**Fri 19/10/18**	
Discussion	11 days	Tue 24/07/18	Tue 7/08/18	
Abstract	6 days	Wed 8/08/18	Wed 15/08/18	
Conclusion	6 days	Thu 16/08/18	Thu 23/08/18	
Recommendations	6 days	Fri 24/08/18	Fri 31/08/18	
Review	11 days	Mon 3/09/18	Mon 17/09/18	
Submission	1 day	Fri 19/10/18	Fri 19/10/18	
Thesis Paper	21 days	Tue 18/09/18	Tue 16/10/18	



Appendix L – Project WBS



Appendix M - Sample Mix Design

Original Mix			
Volume required	0.01131	GPC30	
GPC	Fly Ash	5.04 kgs	
	Sodium Silicate	1.80 kgs	
	Sodium Hydroxide	0.72 kgs	
Super Plasticiser	20% Solution	0.08 kgs	
Fine Aggregate	Sand	6.46 kgs	
	Crumb Rubber	0.00 kgs	
Course Aggregate	Course Aggregate	14.06 kgs	
Water		0.55 kgs	
		28.70 kgs	

Original Mix (Ratio)			
Volume (Standard)	1m3	GPC30	Amended GPC
GPC	Fly Ash	445.76 kgs	
	Sodium Silicate	159.20 kgs	
	Sodium Hydroxide	63.68 kgs	
Super Plasticiser	20% Solution	6.73 kgs	
Fine Aggregate	Sand	571.18 kgs	
	Crumb Rubber	0.00 kgs	
Course Aggregate	Course Aggregate	1243.10 kgs	
Water		48.28 kgs	
		2537.94 kgs	0.00 kgs

7 day testing Results (80deg C)							
GPC30 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	102.30 mm	196.50 mm	3.616 kg	0.00161512 m^3	2238.848561	30.48 MPa	250.50 KN
Sample 2	102.23 mm	197.23 mm	3.650 kg	0.0016189 m^3	2254.619645	30.32 MPa	250.40 KN
Sample 3	102.30 mm	197.32 mm	3.634 kg	0.00162186 m^3	2240.643006	29.09 MPa	239.10 KN
				0.00161862 m^3	2244.703737	29.96 MPa	246.67 KN

7 day testing Results (80deg C)					40%	98.67
GPC30 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	102.47 mm	196.51 mm	3.642 kg	0.00162057 m^3	2247.356302	16002.74 MPa
Sample 5	102.19 mm	196.86 mm	3.647 kg	0.0016146 m^3	2258.767877	15547.49 MPa
Sample 6	102.25 mm	195.33 mm	3.628 kg	0.00160393 m^3	2261.943817	16110.02 MPa
				0.00161303 m^3	2256.022665	15886.75 MPa

7 day testing Results (80deg C)							
GPC30 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	102.47 mm	196.51 mm	3.642 mm	0.00162057 m^3	2247.356302	2.90 MPa	91.81 KN
Sample 5	102.19 mm	196.86 mm	3.647 mm	0.0016146 m^3	2258.767877	2.55 MPa	80.76 KN
Sample 6	102.25 mm	195.33 mm	3.628 mm	0.00160393 m^3	2261.943817	2.86 MPa	89.52 KN
				0.00161303 m^3	2256.022665	2.77 MPa	87.36 KN

Original Mix			
Volume required		0.01131	GPC30
GPC	Fly Ash	5.04 kgs	
	Sodium Silicate	1.80 kgs	
	Sodium Hydroxide	0.72 kgs	
Super Plasticiser	20% Solution	0.08 kgs	
Fine Aggregate	Sand	6.14 kgs	
	Crumb Rubber	0.14 kgs	
Course Aggregate	Course Aggregate	14.06 kgs	
Water		0.55 kgs	
		28.52 kgs	0.00 kgs

Original Mix (Ratio)			
Volume (Standard)	1m3	CR5GPC30	Amended GPC
GPC	Fly Ash	445.76 kgs	
	Sodium Silicate	159.20 kgs	
	Sodium Hydroxide	63.68 kgs	
Super Plasticiser	20% Solution	6.73 kgs	
Fine Aggregate	Sand	542.62 kgs	
	Crumb Rubber	12.63 kgs	
Course Aggregate	Course Aggregate	1243.10 kgs	
Water		48.28 kgs	
		2522.01 kgs	0.00 kgs

7 day testing Results (80deg C)							
GPC30 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	102.21 mm	198.87 mm	3.600 kg	0.00163172 m^3	2206.25938	25.65 MPa	210.40 KN
Sample 2	101.97 mm	199.72 mm	3.623 kg	0.00163101 m^3	2221.324756	25.64 MPa	209.50 KN
Sample 3	102.26 mm	198.10 mm	3.629 kg	0.00162699 m^3	2230.493873	26.43 MPa	217.20 KN
				0.00162991 m^3	2219.359336	25.91 MPa	212.37 MPa

7 day testing Results (80deg C)						84.947
GPC30 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	102.35 mm	199.92 mm	3.625 kg	0.00164483 m^3	2203.871113	14183.05 MPa
Sample 5	102.37 mm	200.10 mm	3.667 kg	0.00164696 m^3	2226.529909	14616.43 MPa
Sample 6	102.34 mm	199.47 mm	3.633 kg	0.00164081 m^3	2214.150328	13465.57 MPa
				0.0016442 m^3	2214.85045	14088.35 MPa

7 day testing Results (80deg C)							
GPC30 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	102.35 mm	199.92 mm	3.625 kg	0.00164483 m^3	2203.871113	2.38 MPa	76.79 KN
Sample 5	102.37 mm	200.10 mm	3.667 kg	0.00164696 m^3	2226.529909	2.65 MPa	85.58 KN
Sample 6	102.34 mm	199.47 mm	3.633 kg	0.00164081 m^3	2214.150328	2.44 MPa	78.57 KN
				0.0016442 m^3	2214.85045	2.49 MPa	80.31 KN

Original Mix			
Volume required	0.01131	GPC30	
GPC	Fly Ash	5.04 kgs	
	Sodium Silicate	1.80 kgs	
	Sodium Hydroxide	0.72 kgs	
Super Plasticiser	20% Solution	0.08 kgs	
Fine Aggregate	Sand	5.81 kgs	
	Crumb Rubber	0.29 kgs	
Course Aggregate	Course Aggregate	14.06 kgs	
Water		0.55 kgs	
		28.34 kgs	0.00 kgs

Original Mix (Ratio)			
Volume (Standard)	1m3	CR10GPC30	Amended GPC
GPC	Fly Ash	445.76 kgs	
	Sodium Silicate	159.20 kgs	
	Sodium Hydroxide	63.68 kgs	
Super Plasticiser	20% Solution	6.73 kgs	
Fine Aggregate	Sand	514.06 kgs	
	Crumb Rubber	25.26 kgs	
Course Aggregate	Course Aggregate	1243.10 kgs	
Water		48.28 kgs	
		2506.08 kgs	0.00 kgs

7 day testing Results (80deg C)							
GPC30 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	102.41 mm	200.57 mm	3.654 kg	0.00165212 m^3	2211.708846	25.89 MPa	213.20 KN
Sample 2	102.32 mm	200.54 mm	3.639 kg	0.00164897 m^3	2206.836207	25.68 MPa	211.10 KN
Sample 3	102.28 mm	201.60 mm	3.619 kg	0.00165639 m^3	2184.875704	25.57 MPa	210.20 KN
				0.00165249 m^3	2201.140252	25.71 MPa	211.50 MPa

7 day testing Results (80deg C)						84.600
GPC30 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	102.18 mm	200.96 mm	3.618 kg	0.0016479 m^3	2195.519316	13816.71 MPa
Sample 5	102.17 mm	201.34 mm	3.656 kg	0.00165069 m^3	2214.825192	13834.99 MPa
Sample 6	102.27 mm	200.37 mm	3.603 kg	0.00164596 m^3	2188.997022	13752.08 MPa
				0.00164819 m^3	2199.78051	13801.26 MPa

7 day testing Results (80deg C)							
GPC30 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	102.18 mm	200.96 mm	3.618 kg	0.0016479 m^3	2195.519316	2.42 MPa	77.84 KN
Sample 5	102.17 mm	201.34 mm	3.656 kg	0.00165069 m^3	2214.825192	2.59 MPa	83.39 KN
Sample 6	102.27 mm	200.37 mm	3.603 kg	0.00164596 m^3	2188.997022	2.38 MPa	76.42 KN
				0.00164819 m^3	2199.78051	2.46 MPa	79.22 KN

Original Mix			
Volume required	0.01131	GPC30	
GPC	Fly Ash	5.04 kgs	
	Sodium Silicate	1.80 kgs	
	Sodium Hydroxide	0.72 kgs	
Super Plasticiser	20% Solution	0.08 kgs	
Fine Aggregate	Sand	5.49 kgs	
	Crumb Rubber	0.43 kgs	
Course Aggregate	Course Aggregate	14.06 kgs	
Water		0.55 kgs	
		28.16 kgs	0.00 kgs

Original Mix (Ratio)			
Volume (Standard)	1m3	CR15GPC30	Amended GPC
GPC	Fly Ash	445.76 kgs	
	Sodium Silicate	159.20 kgs	
	Sodium Hydroxide	63.68 kgs	
Super Plasticiser	20% Solution	6.73 kgs	
Fine Aggregate	Sand	485.50 kgs	
	Crumb Rubber	37.90 kgs	
Course Aggregate	Course Aggregate	1243.10 kgs	
Water		48.28 kgs	
		2490.16 kgs	0.00 kgs

7 day testing Results (80deg C)							
GPC30 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	102.35 mm	199.20 mm	3.581 kg	0.00163891 m^3	2184.989788	23.91 MPa	196.90 KN
Sample 2	102.20 mm	199.68 mm	3.563 kg	0.00163805 m^3	2175.151852	23.49 MPa	192.70 KN
Sample 3	102.31 mm	197.73 mm	3.539 kg	0.00162554 m^3	2177.117885	22.95 MPa	188.60 KN
				0.00163417 m^3	2179.086508	23.45 MPa	192.73 MPa

7 day testing Results (80deg C)						77.093
GPC30 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	102.25 mm	200.11 mm	3.506 kg	0.00164318 m^3	2133.666827	11713.66 MPa
Sample 5	102.41 mm	200.87 mm	3.622 kg	0.00165459 m^3	2189.065481	13560.28 MPa
Sample 6	102.25 mm	199.58 mm	3.559 kg	0.00163883 m^3	2171.673116	13214.13 MPa
				0.00164553 m^3	2164.801808	12829.36 MPa

7 day testing Results (80deg C)							
GPC30 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	102.25 mm	200.11 mm	3.506 mm	0.00164318 m^3	2133.666827	2.15 MPa	68.95 KN
Sample 5	102.41 mm	200.87 mm	3.622 mm	0.00165459 m^3	2189.065481	2.75 MPa	89.02 KN
Sample 6	102.25 mm	199.58 mm	3.559 mm	0.00163883 m^3	2171.673116	2.00 MPa	64.08 KN
				0.00164553 m^3	2164.801808	2.30 MPa	74.02 KN

Original Mix			
Volume required	0.01131	GPC46	
GPC	Fly Ash	4.37 kgs	
	Sodium Silicate	1.16 kgs	
	Sodium Hydroxide	0.46 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	6.28 kgs	
	Crumb Rubber	0.00 kgs	
Course Aggregate	Course Aggregate	14.65 kgs	
GGBS		0.23 kgs	
Water		0.75 kgs	
		27.90 kgs	

Original Mix (Ratio)			
Volume (Standard)	1m3	GPC46	Amended GPC
GPC	Fly Ash	386.65 kgs	
	Sodium Silicate	103.00 kgs	
	Sodium Hydroxide	41.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	555.00 kgs	
	Crumb Rubber	0.00 kgs	
Course Aggregate	Course Aggregate	1295.00 kgs	
GGBS		20.35 kgs	
Water		66.09 kgs	
		2467.09 kgs	0.00 kgs

7 day testing Results (80deg C)							
GPC46 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.92 mm	200.78 mm	3.724 kg	0.00163806 m^3	2273.42437	45.90 MPa	364.30 KN
Sample 2	102.00 mm	200.65 mm	3.712 kg	0.00163957 m^3	2264.01124	46.46 MPa	379.60 KN
Sample 3	101.83 mm	200.90 mm	3.749 kg	0.00163614 m^3	2291.36426	45.77 MPa	362.50 KN
				0.00163792 m^3	2276.266623	46.04 MPa	368.80 KN

7 day testing Results (80deg C)					40%	147.52
GPC46 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.91 mm	201.46 mm	3.746 kg	0.00164328 m^3	2279.583259	22237.68 MPa
Sample 5	101.81 mm	201.53 mm	3.724 kg	0.00164063 m^3	2269.860729	22548.72 MPa
Sample 6	101.95 mm	200.72 mm	3.709 kg	0.00163853 m^3	2263.611249	22788.34 MPa
				0.00164081 m^3	2271.018412	22524.91 MPa

7 day testing Results (80deg C)							
GPC46 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.91 mm	201.46 mm	3.746 mm	0.00164328 m^3	2279.583259	4.60 MPa	
Sample 5	101.81 mm	201.53 mm	3.724 mm	0.00164063 m^3	2269.860729	3.80 MPa	122.59 KN
Sample 6	101.95 mm	200.72 mm	3.709 mm	0.00163853 m^3	2263.611249	2.85 MPa	91.80 KN
				0.00164081 m^3	2271.018412	3.75 KN	107.20 KN

SG Crumb Rubber		1.15	
SG Sand		2.6	
Original Mix			
Volume required		0.01131	CRGPC46 (5%)
GPC	**Fly Ash**	4.37 kgs	
	Sodium Silicate	1.16 kgs	
	Sodium Hydroxide	0.46 kgs	
Super Plasticiser	**20% Solution**	0.00 kgs	
Fine Aggregate	**Sand**	5.96 kgs	
	Crumb Rubber	0.14 kgs	
Course Aggregate	**Course Aggregate**	14.65 kgs	
GGBS		0.23 kgs	
Water		0.75 kgs	
		27.73 kgs	

Original Mix (Ratio)			
Volume (Standard)	1m3	CR5GPC46	Amended GPC
GPC	Fly Ash	386.65 kgs	
	Sodium Silicate	103.00 kgs	
	Sodium Hydroxide	41.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	527.25 kgs	
	Crumb Rubber	12.27 kgs	
Course Aggregate	Course Aggregate	1295.00 kgs	
GGBS		20.35 kgs	
Water		66.09 kgs	
		2451.61 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC46 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.91 mm	199.70 mm	3.685 kg	0.00162893 m^3	2262.225757	41.35 MPa	337.20 KN
Sample 2	101.95 mm	201.28 mm	3.720 kg	0.0016431 m^3	2264.008091	41.60 MPa	339.90 KN
Sample 3	101.98 mm	200.63 mm	3.713 kg	0.00163876 m^3	2265.735344	41.71 MPa	340.80 KN
				0.00163693 m^3	2263.989731	41.55 MPa	339.30 KN

7 day testing Results (80deg C)					40%	135.72
CRGPC46 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.83 mm	200.10 mm	3.672 kg	0.00162963 m^3	2253.275087	20187.03 MPa
Sample 5	102.01 mm	199.85 mm	3.660 kg	0.00163335 m^3	2240.792057	20867.11 MPa
Sample 6	102.02 mm	199.66 mm	3.647 kg	0.00163212 m^3	2234.519643	19662.37 MPa
				0.0016317 m^3	2242.862262	20238.84 MPa

7 day testing Results (80deg C)							
CRGPC46 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.83 mm	200.10 mm	3.672 mm	0.00162963 m^3	2253.275087	3.58 MPa	114.64 KN
Sample 5	102.01 mm	199.85 mm	3.660 mm	0.00163335 m^3	2240.792057	2.63 MPa	84.12 KN
Sample 6	102.02 mm	199.66 mm	3.647 mm	0.00163212 m^3	2234.519643	3.73 MPa	119.40 KN
				0.0016317 m^3	2242.862262	3.31 MPa	106.05 KN

SG Crumb Rubber		1.15	
SG Sand		2.6	
Original Mix			
Volume required		0.01131	CRGPC46 (10%)
GPC	Fly Ash	4.37 kgs	
	Sodium Silicate	1.16 kgs	
	Sodium Hydroxide	0.46 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	5.65 kgs	
	Crumb Rubber	0.28 kgs	
Course Aggregate	Course Aggregate	14.65 kgs	
GGBS		0.23 kgs	
Water		0.75 kgs	
		27.55 kgs	

Original Mix (Ratio)			
Volume (Standard)	1m3	CR10GPC46	Amended GPC
GPC	Fly Ash	386.65 kgs	
	Sodium Silicate	103.00 kgs	
	Sodium Hydroxide	41.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	499.50 kgs	
	Crumb Rubber	24.55 kgs	
Course Aggregate	Course Aggregate	1295.00 kgs	
GGBS		20.35 kgs	
Water		66.09 kgs	
		2436.14 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC46 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	102.28 mm	200.20 mm	3.628 kg	0.00164488 m^3	2205.626064	36.56 MPa	300.50 KN
Sample 2	102.07 mm	200.55 mm	3.625 kg	0.001641 m^3	2209.017893	37.40 MPa	306.20 KN
Sample 3	101.77 mm	200.68 mm	3.673 kg	0.00163243 m^3	2250.025321	37.07 MPa	301.70 KN
				0.00163944 m^3	2221.556426	37.01 MPa	302.80 KN

7 day testing Results (80deg C)					40%	121.12
CRGPC46 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.83 mm	200.30 mm	3.673 kg	0.00163126 m^3	2251.638211	19278.64 MPa
Sample 5	101.88 mm	202.01 mm	3.691 kg	0.0016468 m^3	2241.317709	19001.33 MPa
Sample 6	101.84 mm	199.49 mm	3.623 kg	0.00162498 m^3	2229.567068	18125.10 MPa
				0.00163434 m^3	2240.840996	18801.69 MPa

7 day testing Results (80deg C)							
CRGPC46 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.83 mm	200.30 mm	3.673 mm	0.00163126 m^3	2251.638211	3.60 MPa	115.42 KN
Sample 5	101.88 mm	202.01 mm	3.691 mm	0.0016468 m^3	2241.317709	2.99 MPa	96.59 KN
Sample 6	101.84 mm	199.49 mm	3.623 mm	0.00162498 m^3	2229.567068	2.80 MPa	89.24 KN
				0.00163434 m^3	2240.840996	3.13 MPa	100.42 KN

SG Crumb Rubber		1.15	
SG Sand		2.6	
Original Mix			
Volume required		0.01131	CRGPC46 (15%)
GPC	Fly Ash	4.37 kgs	
	Sodium Silicate	1.16 kgs	
	Sodium Hydroxide	0.46 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	5.34 kgs	
	Crumb Rubber	0.42 kgs	
Course Aggregate	Course Aggregate	14.65 kgs	
GGBS		0.23 kgs	
Water		0.75 kgs	
		27.38 kgs	

Original Mix (Ratio)			
Volume (Standard)	1m3	CR15GPC46	Amended GPC
GPC	Fly Ash	386.65 kgs	
	Sodium Silicate	103.00 kgs	
	Sodium Hydroxide	41.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	471.75 kgs	
	Crumb Rubber	36.82 kgs	
Course Aggregate	Course Aggregate	1295.00 kgs	
GGBS		20.35 kgs	
Water		66.09 kgs	
		2420.66 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC46 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.89 mm	199.02 mm	3.583 kg	0.00162274 m^3	2207.98989	37.47 MPa	305.60 KN
Sample 2	101.73 mm	200.26 mm	3.603 kg	0.00162773 m^3	2213.513015	32.11 MPa	260.80 KN
Sample 3	102.50 mm	201.30 mm	3.647 kg	0.00166104 m^3	2195.605835	32.60 MPa	269.00 KN
				0.00163717 m^3	2205.702913	34.06 MPa	278.47 KN

7 day testing Results (80deg C)					40%	111.39
CRGPC46 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.99 mm	201.31 mm	3.665 kg	0.00164464 m^3	2228.453443	18918.13 MPa
Sample 5	101.84 mm	200.56 mm	3.603 kg	0.0016337 m^3	2205.430003	20320.12 MPa
Sample 6	102.05 mm	200.96 mm	3.657 kg	0.00164371 m^3	2224.843354	20094.17 MPa
				0.00164068 m^3	2219.5756	19777.47 MPa

7 day testing Results (80deg C)							
CRGPC46 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.99 mm	201.31 mm	3.665 mm	0.00164464 m^3	2228.453443	4.05 MPa	130.71 KN
Sample 5	101.84 mm	200.56 mm	3.603 mm	0.0016337 m^3	2205.430003	3.43 MPa	110.09 KN
Sample 6	102.05 mm	200.96 mm	3.657 mm	0.00164371 m^3	2224.843354	3.89 MPa	125.42 KN
				0.00164068 m^3	2219.5756	3.79 MPa	122.07 KN

SG Crumb Rubber		1.15	
SG Sand		2.6	
Original Mix			
Volume required		0.01131	CRGPC46 (20%)
GPC	**Fly Ash**	4.37 kgs	
	Sodium Silicate	1.16 kgs	
	Sodium Hydroxide	0.46 kgs	
Super Plasticiser	**20% Solution**	0.00 kgs	
Fine Aggregate	**Sand**	5.02 kgs	
	Crumb Rubber	0.56 kgs	
Course Aggregate	**Course Aggregate**	14.65 kgs	
GGBS		0.23 kgs	
Water		0.75 kgs	
		27.20 kgs	

Original Mix (Ratio)			
Volume (Standard)	1m3	CR20GPC46	Amended GPC
GPC	Fly Ash	386.65 kgs	
	Sodium Silicate	103.00 kgs	
	Sodium Hydroxide	41.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	444.00 kgs	
	Crumb Rubber	49.10 kgs	
Course Aggregate	Course Aggregate	1295.00 kgs	
GGBS		20.35 kgs	
Water		66.09 kgs	
		2405.19 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC46 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.52 mm	198.21 mm	3.479 kg	0.00160442 m^3	2168.381871	31.82 MPa	257.50 KN
Sample 2	101.62 mm	197.88 mm	3.512 kg	0.00160491 m^3	2188.287316	34.85 MPa	282.50 KN
Sample 3	101.47 mm	198.72 mm	3.525 kg	0.00160697 m^3	2193.574257	33.92 MPa	274.50 KN
				0.00160543 m^3	2183.414481	33.53 MPa	271.50 KN

7 day testing Results (80deg C)						108.6
CRGPC46 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.66 mm	199.08 mm	3.522 kg	0.00161591 m^3	2179.574045	17663.65 MPa
Sample 5	101.55 mm	200.22 mm	3.537 kg	0.00162165 m^3	2181.111492	17558.69 MPa
Sample 6	101.51 mm	198.80 mm	3.531 kg	0.00160888 m^3	2194.693112	17895.29 MPa
				0.00161548 m^3	2185.126216	17705.88 MPa

7 day testing Results (80deg C)							
CRGPC46 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.66 mm	199.08 mm	3.522 mm	0.00161591 m^3	2179.574045	3.07 MPa	97.67 KN
Sample 5	101.55 mm	200.22 mm	3.537 mm	0.00162165 m^3	2181.111492	2.99 MPa	95.67 KN
Sample 6	101.51 mm	198.80 mm	3.531 mm	0.00160888 m^3	2194.693112	3.25 MPa	102.87 KN
				0.00161548 m^3	2185.126216	3.10 MPa	98.74 KN

SG Crumb Rubber	1.15
SG Sand	2.6

Original Mix			
Volume required	0.01131	CRGPC46 (25%)	
GPC	Fly Ash	4.37 kgs	
	Sodium Silicate	1.16 kgs	
	Sodium Hydroxide	0.46 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	4.71 kgs	
	Crumb Rubber	0.69 kgs	
Course Aggregate	Course Aggregate	14.65 kgs	
GGBS		0.23 kgs	
Water		0.75 kgs	
		27.03 kgs	

Original Mix (Ratio)			
Volume (Standard)	1m3	CR25GPC46	Amended GPC
GPC	Fly Ash	386.65 kgs	
	Sodium Silicate	103.00 kgs	
	Sodium Hydroxide	41.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	416.25 kgs	
	Crumb Rubber	61.37 kgs	
Course Aggregate	Course Aggregate	1295.00 kgs	
GGBS		20.35 kgs	
Water		66.09 kgs	
		2389.71 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC46 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.78 mm	200.20 mm	3.519 kg	0.00162884 m^3	2160.431094	29.62 MPa	241.10 KN
Sample 2	101.65 mm	199.40 mm	3.510 kg	0.00161819 m^3	2169.088716	29.87 MPa	242.20 KN
Sample 3	104.13 mm	197.77 mm	3.693 kg	0.00168423 m^3	2192.690202	31.97 MPa	272.10 KN
				0.00164376 m^3	2174.070004	30.49 MPa	251.80 KN

7 day testing Results (80deg C)						100.72
CRGPC46 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.89 mm	200.62 mm	3.562 kg	0.00163579 m^3	2177.542716	15856.46 MPa
Sample 5	101.44 mm	199.90 mm	3.490 kg	0.00161555 m^3	2160.251276	15897.71 MPa
Sample 6	104.15 mm	198.80 mm	3.706 kg	0.00169365 m^3	2188.16771	16560.21 MPa
				0.00164833 m^3	2175.320567	16104.79 MPa

7 day testing Results (80deg C)							
CRGPC46 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.89 mm	200.62 mm	3.562 mm	0.00163579 m^3	2177.542716	3.14 MPa	100.82 KN
Sample 5	101.44 mm	199.90 mm	3.490 mm	0.00161555 m^3	2160.251276	2.92 MPa	93.00 KN
Sample 6	104.15 mm	198.80 mm	3.706 mm	0.00169365 m^3	2188.16771	3.15 MPa	102.59 KN
				0.00164833 m^3	2175.320567	3.07 MPa	98.80 KN

Original Mix			
Volume required		0.01131	GPC58
GPC	Fly Ash	4.07 kgs	
	Sodium Silicate	1.39 kgs	
	Sodium Hydroxide	0.55 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	6.05 kgs	
	Crumb Rubber	0.00 kgs	
GGBS		0.45 kgs	
Course Aggregate	14mm	6.28 kgs	
	10mm	4.86 kgs	
	7mm	2.77 kgs	
Water		0.57 kgs	
		26.99 kgs	0.00 kgs

Original Mix (Ratio)			
Volume (Standard)	1m3	GPC58	Amended GPC
GPC	Fly Ash	360.00 kgs	
	Sodium Silicate	122.50 kgs	
	Sodium Hydroxide	49.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	535.00 kgs	
	Crumb Rubber	0.00 kgs	
GGBS		40.00 kgs	
Course Aggregate	14mm	555.00 kgs	
	10mm	430.00 kgs	
	7mm	245.00 kgs	
Water		50.38 kgs	
		2386.88 kgs	0.00 kgs

7 day testing Results (80deg C)							
GPC58 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.50 mm	199.17 mm	3.68 kg	0.00161156 m^3	2282.263768	57.86 MPa	468.20 KN
Sample 2	101.72 mm	199.12 mm	3.68 kg	0.00161815 m^3	2275.444862	55.90 MPa	454.10 KN
Sample 3	101.45 mm	197.00 mm	3.61 kg	0.00159243 m^3	2269.488247	58.71 MPa	474.10 KN
				0.00160738 m^3	2275.732292	57.49 MPa	465.47 KN

7 day testing Results (80deg C)					40%	186.19
GPC58 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.61 mm	196.38 mm	3.61 kg	0.00159243 m^3	2268.861166	Error
Sample 5	101.86 mm	197.67 mm	3.63 kg	0.00161079 m^3	2254.178284	24502.67 MPa
Sample 6	101.85 mm	194.70 mm	3.56 kg	0.00158627 m^3	2242.993651	24766.15 MPa
				0.0015965 m^3	2255.344367	24634.41 MPa

7 day testing Results (80deg C)							
GPC58 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 7	101.96 mm	198.19 mm	3.65 kg	0.0016182 m^3	2254.979462	4.96 MPa	157.37 KN
Sample 8	101.61 mm	199.55 mm	3.66 kg	0.00161813 m^3	2260.628429	4.02 MPa	127.91 KN
Sample 9	101.80 mm	198.48 mm	3.65 kg	0.00161548 m^3	2258.768251	4.67 MPa	148.09 KN
				0.00161727 m^3	2258.125381	4.55 MPa	144.46 KN

Original Mix			
Volume required	0.01131	GPC58	
GPC	Fly Ash	4.07 kgs	
	Sodium Silicate	1.39 kgs	
	Sodium Hydroxide	0.55 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	5.75 kgs	
	Crumb Rubber	0.13 kgs	
GGBS		0.45 kgs	
Course Aggregate	14mm	6.28 kgs	
	10mm	4.86 kgs	
	7mm	2.77 kgs	
Water		0.57 kgs	
		26.83 kgs	0.00 kgs

Original Mix (Ratio)			
Volume (Standard)	1m3	CR5GPC58	Amended GPC
GPC	Fly Ash	360.00 kgs	
	Sodium Silicate	122.50 kgs	
	Sodium Hydroxide	49.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	508.25 kgs	
	Crumb Rubber	11.83 kgs	
GGBS		40.00 kgs	
Course Aggregate	14mm	555.00 kgs	
	10mm	430.00 kgs	
	7mm	245.00 kgs	
Water		50.38 kgs	
		2371.96 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC58 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.95 mm	200.27 mm	3.71 kg	0.00163486 m^3	2271.755876	45.89 MPa	375.00 KN
Sample 2	101.87 mm	201.15 mm	3.72 kg	0.00163947 m^3	2268.420941	45.52 MPa	371.20 KN
Sample 3	101.97 mm	200.90 mm	3.73 kg	0.00164065 m^3	2272.276866	44.41 MPa	362.90 KN
				0.00163832 m^3	2270.817894	45.27 MPa	369.70 KN

7 day testing Results (80deg C)					40%	147.88
CRGPC58 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.91 mm	200.31 mm	3.71 kg	0.0016339 m^3	2268.801343	25559.26 MPa
Sample 5	101.90 mm	201.44 mm	3.72 kg	0.0016428 m^3	2266.865277	25153.86 MPa
Sample 6	102.00 mm	200.32 mm	3.72 kg	0.00163687 m^3	2274.461028	25038.79 MPa
				0.00163786 m^3	2270.042549	25250.64 MPa

7 day testing Results (80deg C)							
CRGPC58 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.91 mm	200.31 mm	3.71 kg	0.0016339 m^3	2268.801343	3.06 MPa	98.20 KN
Sample 5	101.90 mm	201.44 mm	3.72 kg	0.0016428 m^3	2266.865277	3.78 MPa	121.70 KN
Sample 6	102.00 mm	200.32 mm	3.72 kg	0.00163687 m^3	2274.461028	3.88 MPa	124.40 KN
				0.00163786 m^3	2270.042549	3.83 MPa	123.05 KN

Original Mix			
Volume required	0.01131	GPC58	
GPC	Fly Ash	4.07 kgs	
	Sodium Silicate	1.39 kgs	
	Sodium Hydroxide	0.55 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	5.45 kgs	
	Crumb Rubber	0.27 kgs	
GGBS		0.45 kgs	
Course Aggregate	14mm	6.28 kgs	
	10mm	4.86 kgs	
	7mm	2.77 kgs	
Water		0.57 kgs	
		26.66 kgs	0.00 kgs

Original Mix (Ratio)			
Volume (Standard)	1m3	CR10GPC58	Amended GPC
GPC	Fly Ash	360.00 kgs	
	Sodium Silicate	122.50 kgs	
	Sodium Hydroxide	49.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	481.50 kgs	
	Crumb Rubber	23.66 kgs	
GGBS		40.00 kgs	
Course Aggregate	14mm	555.00 kgs	
	10mm	430.00 kgs	
	7mm	245.00 kgs	
Water		50.38 kgs	
		2357.04 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC58 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	102.15 mm	201.50 mm	3.69 kg	0.00165136 m^3	2232.10005	43.58 MPa	357.50 KN
Sample 2	101.96 mm	201.71 mm	3.73 kg	0.00164694 m^3	2263.596112	38.77 MPa	316.80 KN
Sample 3	101.84 mm	202.40 mm	3.74 kg	0.00164868 m^3	2270.903446	46.28 MPa	376.70 KN
				0.00164899 m^3	2255.533202	42.88 MPa	350.33 KN

7 day testing Results (80deg C)					40%	140.13
CRGPC58 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.83 mm	201.48 mm	3.69 kg	0.00164087 m^3	2250.63981	24026.55 MPa
Sample 5	101.82 mm	202.85 mm	3.74 kg	0.0016517 m^3	2262.517875	21006.41 MPa
Sample 6	102.05 mm	201.74 mm	3.74 kg	0.00165009 m^3	2264.117448	22906.03 MPa
				0.00164755 m^3	2259.091711	22646.33 MPa

7 day testing Results (80deg C)							
CRGPC58 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.83 mm	201.48 mm	3.69 kg	0.00164087 m^3	2250.63981	4.12 MPa	132.60 KN
Sample 5	101.82 mm	202.85 mm	3.74 kg	0.0016517 m^3	2262.517875	3.40 MPa	110.20 KN
Sample 6	102.05 mm	201.74 mm	3.74 kg	0.00165009 m^3	2264.117448	3.54 MPa	114.50 KN
				0.00164755 m^3	2259.091711	3.69 MPa	119.10 KN

Original Mix			
Volume required	0.01131	GPC58	
GPC	Fly Ash	4.07 kgs	
	Sodium Silicate	1.39 kgs	
	Sodium Hydroxide	0.55 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	5.14 kgs	
	Crumb Rubber	0.40 kgs	
GGBS		0.45 kgs	
Course Aggregate	14mm	6.28 kgs	
	10mm	4.86 kgs	
	7mm	2.77 kgs	
Water		0.57 kgs	
		26.49 kgs	0.00 kgs

Original Mix (Ratio)			
Volume (Standard)	1m3	CR15GPC58	Amended GPC
GPC	Fly Ash	360.00 kgs	
	Sodium Silicate	122.50 kgs	
	Sodium Hydroxide	49.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	454.75 kgs	
	Crumb Rubber	35.50 kgs	
GGBS		40.00 kgs	
Course Aggregate	14mm	555.00 kgs	
	10mm	430.00 kgs	
	7mm	245.00 kgs	
Water		50.38 kgs	
		2342.12 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC58 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.85 mm	200.43 mm	3.66 kg	0.00163296 m^3	2243.782676	45.62 MPa	371.30 KN
Sample 2	101.79 mm	200.12 mm	3.65 kg	0.00162851 m^3	2241.925768	50.20 MPa	408.60 KN
Sample 3	101.87 mm	200.20 mm	3.68 kg	0.00163172 m^3	2254.671219	56.59 MPa	461.50 KN
				0.00163106 m^3	2246.793221	50.80 MPa	413.80 KN

7 day testing Results (80deg C)					40%	165.52
CRGPC58 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.77 mm	202.14 mm	3.72 kg	0.0016443 m^3	2259.316772	23652.11 MPa
Sample 5	101.91 mm	202.56 mm	3.70 kg	0.00165226 m^3	2239.363273	23455.28 MPa
Sample 6	101.78 mm	201.24 mm	3.70 kg	0.0016373 m^3	2258.592199	24272.28 MPa
				0.00164462 m^3	2252.424081	23793.22 MPa

7 day testing Results (80deg C)							
CRGPC58 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.77 mm	202.14 mm	3.72 kg	0.0016443 m^3	2259.316772	5.35 MPa	173.00 KN
Sample 5	101.91 mm	202.56 mm	3.70 kg	0.00165226 m^3	2239.363273	4.75 MPa	154.17 KN
Sample 6	101.78 mm	201.24 mm	3.70 kg	0.0016373 m^3	2258.592199	4.98 MPa	160.36 KN
				0.00164462 m^3	2252.424081	5.03 MPa	162.51 KN

Original Mix			
Volume required	0.01131	GPC58	
GPC	Fly Ash	4.07 kgs	
	Sodium Silicate	1.39 kgs	
	Sodium Hydroxide	0.55 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	4.24 kgs	
	Crumb Rubber	0.80 kgs	
GGBS		0.45 kgs	
Course Aggregate	14mm	6.28 kgs	
	10mm	4.86 kgs	
	7mm	2.77 kgs	
Water		0.57 kgs	
		25.98 kgs	0.00 kgs

Original Mix (Ratio)			
Volume (Standard)	1m3	CR30GPC58	Amended GPC
GPC	Fly Ash	360.00 kgs	
	Sodium Silicate	122.50 kgs	
	Sodium Hydroxide	49.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	374.50 kgs	
	Crumb Rubber	70.99 kgs	
GGBS		40.00 kgs	
Course Aggregate	14mm	555.00 kgs	
	10mm	430.00 kgs	
	7mm	245.00 kgs	
Water		50.38 kgs	
		2297.37 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC58 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.27 mm	200.00 mm	3.495 kg	0.00161095 m^3	2169.530116	29.03 MPa	234.00 KN
Sample 2	101.75 mm	199.50 mm	3.508 kg	0.00162219 m^3	2162.509219	34.34 MPa	279.50 KN
Sample 3	104.17 mm	198.72 mm	3.700 kg	0.00169362 m^3	2184.665427	39.20 MPa	334.30 KN
				0.00164225 m^3	2172.234921	34.19 MPa	282.60 KN

7 day testing Results (80deg C)					40%	113.04
CRGPC58 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.46 mm	198.20 mm	3.491 kg	0.00160245 m^3	2178.545332	17553.92 MPa
Sample 5	101.61 mm	201.04 mm	3.599 kg	0.00163022 m^3	2207.682357	20159.78 MPa
Sample 6	104.08 mm	198.91 mm	3.687 kg	0.00169231 m^3	2178.673103	17772.96 MPa
				0.00164166 m^3	2188.300264	18495.55 MPa
					2182.945149	

7 day testing Results (80deg C)							
CRGPC58 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.46 mm	198.20 mm	3.491 kg	0.00160245 m^3	2178.545332	3.40 MPa	107.49 KN
Sample 5	101.61 mm	201.04 mm	3.599 kg	0.00163022 m^3	2207.682357	2.74 MPa	88.02 KN
Sample 6	104.08 mm	198.91 mm	3.687 kg	0.00169231 m^3	2178.673103	3.49 MPa	113.39 KN
				0.00164166 m^3	2188.300264	3.21 MPa	102.97 KN

Original Mix			
Volume required		0.01131	GPC58
GPC	Fly Ash	4.07 kgs	
	Sodium Silicate	1.39 kgs	
	Sodium Hydroxide	0.55 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	3.93 kgs	
	Crumb Rubber	0.94 kgs	
GGBS		0.45 kgs	
Course Aggregate	14mm	6.28 kgs	
	10mm	4.86 kgs	
	7mm	2.77 kgs	
Water		0.57 kgs	
		25.81 kgs	0.00 kgs

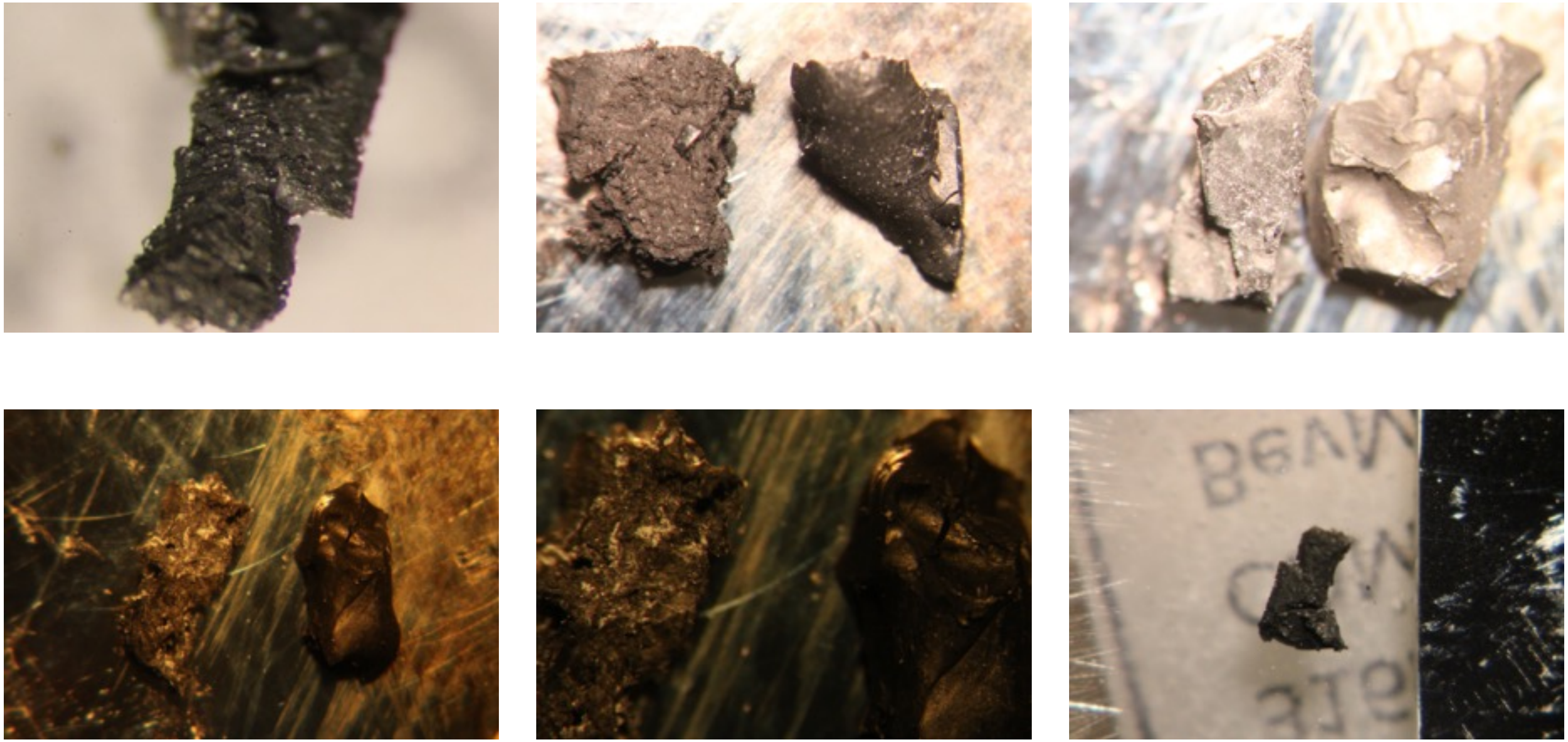
Original Mix (Ratio)			
Volume (Standard)	1m3	CR35GPC58	Amended GPC
GPC	Fly Ash	360.00 kgs	
	Sodium Silicate	122.50 kgs	
	Sodium Hydroxide	49.00 kgs	
Super Plasticiser	20% Solution	0.00 kgs	
Fine Aggregate	Sand	347.75 kgs	
	Crumb Rubber	82.82 kgs	
GGBS		40.00 kgs	
Course Aggregate	14mm	555.00 kgs	
	10mm	430.00 kgs	
	7mm	245.00 kgs	
Water		50.38 kgs	
		2282.45 kgs	0.00 kgs

7 day testing Results (80deg C)							
CRGPC58 Comp	Diameter	Height	Weight	Volume	Density	Compressive Strength	Force Applied
Sample 1	101.74 mm	200.23 mm	3.517 kg	0.00162781 m^3	2160.577619	33.03 MPa	268.30 KN
Sample 2	101.33 mm	199.11 mm	3.459 kg	0.00160568 m^3	2154.227289	31.94 MPa	257.40 KN
Sample 3	104.10 mm	197.80 mm	3.621 kg	0.00168352 m^3	2150.85383	33.29 MPa	282.30 KN
				0.001639 m^3	2155.219579	32.75 MPa	269.33 KN

7 day testing Results (80deg C)					40%	107.73
CRGPC58 Mod	Diameter	Height	Weight	Volume	Density	Modulus
Sample 4	101.14 mm	199.65 mm	3.515 kg	0.001604 m^3	2191.392823	15558.72 MPa
Sample 5	101.42 mm	200.06 mm	3.490 kg	0.00161621 m^3	2159.374998	15784.51 MPa
Sample 6	103.87 mm	200.45 mm	3.707 kg	0.00169854 m^3	2182.460443	15857.66 MPa
				0.00163958 m^3	2177.742755	15733.63 MPa
					2170.235029	

7 day testing Results (80deg C)							
CRGPC58 Flex	Diameter	Height	Weight	Volume	Density	Ind Tensle Strength	Force Applied
Sample 4	101.14 mm	199.65 mm	3.515 kg	0.001604 m^3	2191.392823	3.08 MPa	97.68 KN
Sample 5	101.42 mm	200.06 mm	3.490 kg	0.00161621 m^3	2159.374998	3.41 MPa	108.76 KN
Sample 6	103.87 mm	200.45 mm	3.707 kg	0.00169854 m^3	2182.460443	3.73 MPa	122.05 KN
				0.00163958 m^3	2177.742755	3.41 MPa	109.50 KN

Appendix N - CR and Pre-Treated CR Images



Appendix O - Literature Review

Properties of Geopolymer Concrete

Geopolymer concrete is made with an alkaline activated binder that completely replaces the Ordinary Portland Cement (OPC). The Geopolymer is made with pozzolanic materials such as Fly Ash (FA), Ground Granulate Blast Furnace Slag (GGBS) or metakaolin. This material is then activated with a highly alkaline solution made up of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3). *Figure 1* shows Conceptual model for the Alkaline Activation Process.

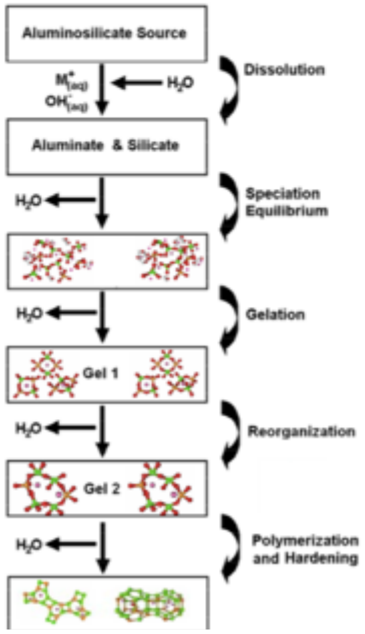


Figure 16. Conceptual model for Alkaline Activation Process (Fernandez-Jimenez, 2011).

Mechanical Properties

GPC has been receiving extensive research owing to is métier properties over Ordinary Portland Concrete (OPC) consisting of lower creep, lower shrinkage, better fire and acid resistance, and resistance to sulfate attack.

Through experimental research (Vargas, 2011) it was found that GPC undergoes transient creep, contractive and expansive volume changes whilst maintaining its structural integrity at elevated temperatures (up to 1000°C). Although the residual strength properties, when returned to ambient temprature, are lower they are significantly higher than that of OPC concrete.

The tensile strength of concrete depends on mix composition factors such as aggregate, grade and aggregate to binder ratio and can be measured in two ways, flexural tensile strength and splitting tensile strength. However, the influence from these compositional factors governing tensile strength is different between the two methods. Standards have been developed to predict the tensile strength of concrete based on the compressive strength (Mendis, 2017). Splitting tensile strength of GPC has been found, through experimental models (E. Ivan Diaz-Loya, 2011), to be similar to the equation given by ACI 318-11, for OPC to estimate the modulus of elasticity:

$f_{ctm} = 0.556\,(f_c')^{0.5}$ MPa (ACI Committee 318-11, 2011) *Equation 1*

$f_{ctm} = 0.59\,(f_c')^{0.5}$ MPa (ACI Committee 363-92, 1992) *Equation 2*

Where f_{ctm} is the tensile flexural strength and f_c' is the compressive strength of OPC concrete after 28 days of curing. From my experimental research this has been verified to be accurate within 5% for 7-day strength with GPC. A crude analysis could be made that f_{ctm} is approximately 8-10% of f_c' at 7-day strength for GPC.

Modulus of elasticity depends on the compressive strength of the concrete similar to that of tensile strength. ACI 318-11 represents a static elastic modulus relative to the compressive strength of normal weight concrete as:

$E_c = 4733\ (f_c')^{0.5}$ MPa (ACI Committee 318-08, 2008) *Equation 3*

Where E_c is the static elastic modulus and f_c' is the compressive strength. However, GPC mixes can exhibit a wide range of density values depending on the Fly Ash fitness and therefore a wider range of E_c is noticed. Therefore, an experimental interaction between the density and the compressive strength of GPC can give a predictor of the elastic modulus as researched in (Jannie S.J. van Deventer, 2012) & (Mendis, 2017):

$E_c = 33(w)^{1.5}\ (f_c')^{0.5}$ Pa (ACI Committee 318-11, 2011) *Equation 4*

$E_c = 0.043(w)^{1.5}\ (f_c')^{0.5}$ MPa (AS 3600, 2009) *Equation 5*

Where w is the density of the GPC. From my experimental research this has also been verified within 20% variance with a constant of approximately 0.0301 being more suitable for 7-day strength. From the Standards (AS and ACI) mechanical properties of OPC concrete can be determined to within 20% of their actual mechanical values using the its compressive strength. Previous research is heading towards verifying that GPC can also use these standards. However there has not been research performed to properly establish CRGPC's application for these equations or whether different constants need to be established.

Mix Design of Geopolymer Concrete

Geopolymer Concrete has many properties that can be varied and manipulated to produce an effective mix design. The core mix design elements include Fly Ash, Na_2SiO_3, NaOH, water, fine and course aggregates. Additional elements used for this research include GGBS and super plasticiser.

The experimental research of this project will be carried using Class F Fly Ash as preferred over Class C Fly Ash. The main differences that dictate selection of either Class F or Class C Fly Ash is the chemical composition particularly the pozzolanic and calcium oxide content. A pozzolan is a class of siliceous and aluminous materials (silica oxide, iron oxide and alumina oxide) which, when powdered and combined with water, react to form compounds with cementitious properties. Class F Fly Ash contains a minimum of 70% pozzolanic compounds

(ASTM C618, 2017) and contains low levels of calcium oxide (0-16%) as seen in *Appendix G*. Whilst Class C Fly Ash (*Appendix H*) contains 50-70% pozzolanic compounds and contains calcium oxide over 20%. When using Alkaline Activated Fly Ash it must be below 45 microns otherwise it is classified as inert.

Many papers have been written discussing the effect on GPC by changing the molarity of the Sodium Hydroxide in the mix. Studies have been performed supplementing 8M, 10M, 12M and 16M NaOH. Mixing of NaOH can be calculated by either chemical analysis (does not account for losses and change in specific density of water used or ambient pressure) or by experimental analysis of molarity once mixed (more accurate, accounts for losses). Hardjito and Rangan (Rangan, 2005) (Boral Limited 2013, 2013) performed the experimental analysis and determined the amount of sodium hydroxide flakes used by weight per kg of solution for each of the focused molarities as given in *Table 2*. To reduce variables in the different mix designs for this research it was decided to use a consistent 16M NaOH mixture.

Table 10. Mix Design for Molarity of NaOH (Junaid, 2015)

Molarity of NaOH Solution (M)	Weight of NaOH Flakes per kg of Solution (g)
8	262
10	314
12	361
16	444

The effect on Compressive strength can be seen *Figure 2* (J. Temuujin∗, 2009), due to the sodium silicate to NaOH ratio used in a mix, is quite substantial and needs to be closely monitored. This can also be seen in the experimental research performed by (Gum Sung Ryu a, 2013) where Al/Si ratios between 1.6 and 2.15 exhibit higher compressive strengths. When altering a design mix to increase or decrease the compressive strength it is come practice to manipulate not only the ratio of the solid (Fly Ash) to alkaline solution (S/L) but the ratio between the sodium silicate and sodium hydroxide (P. Duxson, 2007). Knowing what side of the curve ratio you are on is critical to make correct adjustments.

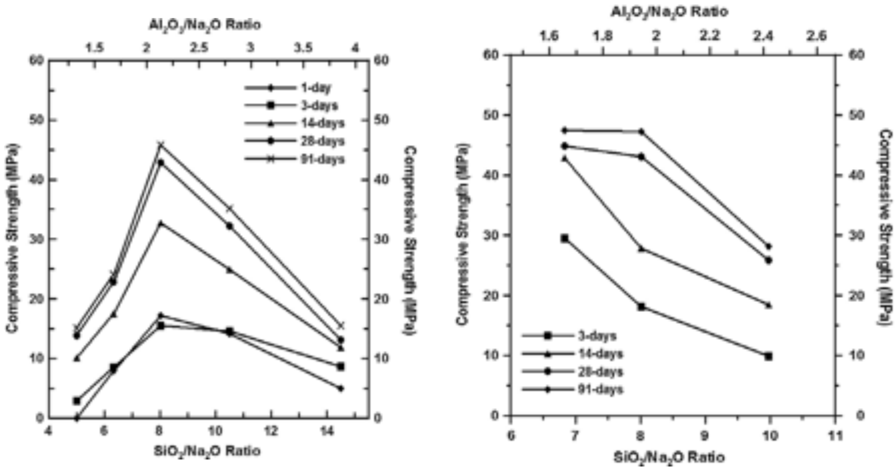


Figure 17. Compressive strength Al2O3/Na2O ratio (sodium silicate to NaOH)

The results concluded that both S/L and Na_2SiO_3/NaOH ratios affected the GPC compressive strength.

Selection of Fine and Coarse aggregates for mix design can play a major role on the final characteristic properties of a concrete mix. The aggregate selection, grading and ratio to binder can affect all of the characteristic properties of the concrete.

Due to the chemical reactions that occur in GPC naphthalene sulphonate based superplasticiser must be utilised to avoid additional processes occurring. Super plasticisers are generally determined as a percentage of binding solids (combination of FA, GGBS and Kaolin in design mix).

Another pozzolanic material that can be used, in whole or part, to create GPC is Ground Granulated Blast Furnace Slag (GGBS). GGBS is a made from the remnants of steel manufacturing which contain the aluminates and silicates of the ore and coke ash. GGBS can be added to a mix to lower heat hydration, resist ground water abrasion and fight other hostile environmental conditions. It can be added to fly ash, of up to 400 kg/m^3, in a range from 10-80 kg/m^3 (BERNAL, 2012) (DEB, 2014).

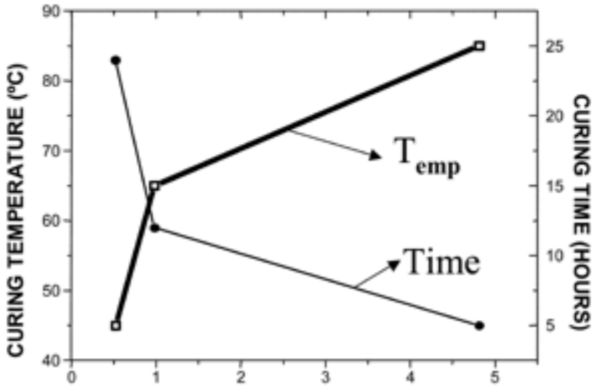


Figure 18. Maximum rate of mechanical strength gaining versus curing time and curing temperature (E.I. Diaz, 2010).

Curing time and temperature play an important part in producing the design mix's desired mechanical properties. *Figure 3* Shows the rate of strength gained for different curing temperatures and time.

Initial mix designs for the three core mixes that were used for this project were liberated from research papers that have been published. Different approaches have been taken with the development of GPC mix design from statistical/process driven designs to purely experimental research.

GPC32 was driven from a statistical process derived from (Subhash V. Patankar, 2015) and a spreadsheet to produce the mix design as seen in *Appendix C*. Although this design worked well to produce a 32MPa mix, it relied on increasing the Fly Ash content to produce higher compressive strength concrete which failed to be appropriate for the conditions set. GPC58 was developed using the research from (psuvarnas, 2009). This was selected as the addition of GGBS and reduction of Fly Ash not only yields higher compressive strengths but also provides a different mix composition to coincide with the aim of this research project. Slight variations where made with the portions of NaOH molarity, super plasticiser, water content, temperature and time inside the curing chamber. This was required to achieve the workability and target compressive strength using the Fly Ash available and project fixed variables that were set. GPC40 was developed experimentally based on the results from GPC32 and GPC58 trials. Adjustments were made to the quantity of GGBS used, alkaline solution and coarse aggregate reduced to single source. Although not necessarily ideal mix designs, using these three mixes provides an appropriate range of variables to meet the aim and purpose of this experimental research.

There are many design parameters that can be altered or modified to create specific mechanical strength geopolymer concrete. However, there are inherent parameters in the Fly Ash that dictate the characteristic properties of the mixed GPC. The most important of which are the fineness and chemical composition. The fineness of the FA is important as if the particles are greater than 45micron it is considered that they will be inert and not react to form part of the binder matrix. This essentially has then added as addition fine aggregate. The chemical composition of Fly Ash particularly oxide contents effect characteristic properties. *Table 3* shows the Oxide Composition of the Fly Ash that is being used in this document's experimental research.

Table 11. Oxide Composition of Fly Ash by XRF

Oxides	%
CaO	1.6
SiO_2	65.5
Al_2O_3	24.5
Fe_2O_3	3.1
SO_3	0.1
MgO	0.5
Na_2O	0.45
K_2O	1.43
SrO	<0.1
TiO_2	1.0
P_2O_5	0.3
Mn_2O_3	<0.1

Calcium Oxide in particular is critical in developing the required characteristic properties. The process being used to create the GPC governs whether a high or low level of CaO is desirable. If the GPC is the be cured at ambient temperatures a FA with higher levels of CaO would be preferred, such as Class C FA. Additional Calcium compounds can result in improved dissolution of the FA and subsequent geopolymerisation (Chowdhury, 2013). However, if the GPC mix is to be cured at elevated temperatures (eg 80°C) a FA with low CaO levels is favoured. At elevated curing temperatures with excessive CaO an insufficient development of a three-dimensional geopolymeric aluminosilicate network is created by the presence of the calcium in the aluminosilicate network (Kiatsuda Somna, 2011) & (Chowdhury, 2013).

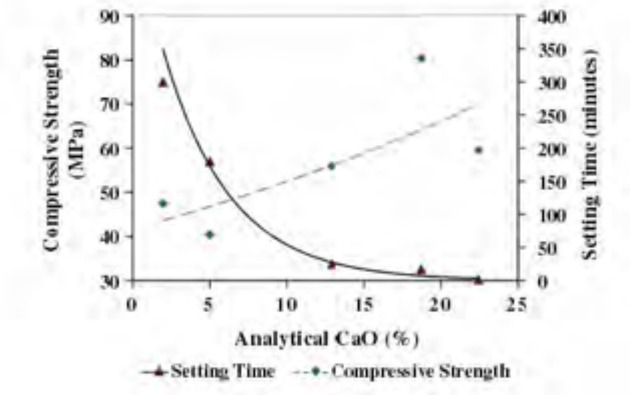


Figure 19. Correlation Between CaO%, Compressive Strength and Setting Times (AS 1141.5-2000, 2016).

Figure 4 shows the relationship of CaO content to compressive strengths using elevated curing temperatures. For this Experimental research a raised temperature curing procedure has been selected and therefore a low calcium oxide content FA is required to achieve appropriate compressive strengths.

Comparison of Geopolymer Concrete to Ordinary Portland Cement
Environmental Differences

When looking at environmental impacts of Ordinary Portland Cement there are not only continuous chemical effects when mixing but also manufacturing consequences that are cause for serious concern. The OPC manufacturing process is expensive, requires raw materials which involves the destruction of precious resources and heating at very high temperatures causing emissions of CO_2 and pollutant gases. Alternatively, GPC is low cost, easy to process and produces 70% less life cycle greenhouse gas emissions (Davidovits, 2015). It is important to note that Fly Ash is a particle by product of coal-fired boilers and if using coal as a source and fuel to create power ceased to be used, GPC Fly Ash would not be readily available without significant environmental effects. Of the 33 Coal fired power stations in Australia nine have closed between 2010-2016. The Climate Change Authority has recommended that by 2030 all brown coal stations be closed and over two-thirds of black coal stations be decommissioned (Parliment of Australia, 2017).

Mechanical Property Differences

When compared to OPC, Alkaline Activated Fly Ash binders gives GPC a set of equivalent or superior mechanical and chemical properties to those of OPC concrete. Properties include elevated acid resistance and resistance to sulphur attack, low shrinkage, increased fire resistance, early strength gain, high compressive and flexural strengths (Gourley T, 2005).

Compressive strength tests conducted from a vaste range of GPC research have demonstrated a wide range compressive strength from 20 MPa (DH) to 80 MPa. Typical construction applications require a 28-day compressive strength of 25–50 MPa. It has been demonstrated that, depending on the binder to aggregate ratio, that GPC achieves a much higher rate of strength gain when compared to OPC. GPC achieves approximately 90% of its final strength within 72 hours, whereas OPC has only achieved approximately 50% of its final strength by this stage and taking between 7-14 days to achieve the 90% benchmark (A. M. Mustafa Al Bakri, 2013).

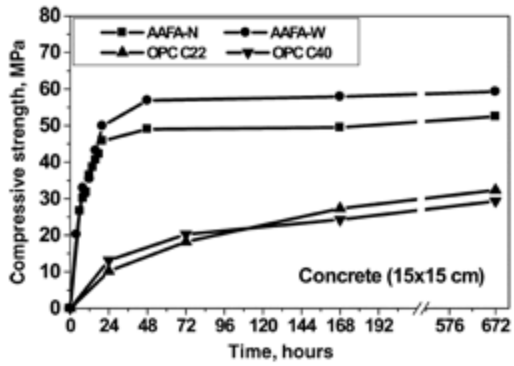


Figure 20. Development of Compressive Strength with Time for AAFA and OPC (Ana M. Fernández-Jiménez, 2006) (E.I. Diaz, 2010)

Research has shown that the compressive strength is affected by both solid to liquid and sodium hydroxide to sodium silicate ratios. Both the S/L and Na2SiO3/NaOH ratios influenced the workability of the design mix as well as the quantity of additional water added as a ratio of the water to fly ash (W/FA). OPC concrete utilises slump testing as a form of workability analysis which is not suitable for GPC as it inherently moves differently creating erroneous results. Properly designed GPC relies heavily of the S/L, Na2SiO3/NaOH and W/FA ratios. Altering any of these ratios to allow for workability can drastically alter the characteristic properties required by the design. As such, viscosity modifying agents and super plasticisers are added to assist with acquiring the workability required. It is important that naphthalene sulphonate based superplasticiser are used with geopolymer concrete as polycarboxylate ether (used in OPC) will have detrimental effects on the compressive strength of the concrete. Ratios of above 1% of binding solids (combination of FA, GGBS and Kaolin) as superplasticiser should be avoided to reduce effects.

Experimental research carried out on the strength of small samples (Bakharev, 2006) (Rickard W, 2012) has shown evidence that geopolymer concrete has better resistance to fire than OPC concrete. Compressive strength, modulus of elasticity and splitting tensile strength have been tested with an exposure to 1000 and these values have reported substantially higher values compared to OPC (Junaid, 2015).

When comparing the two binders, Ordinary Portland Cement and Alkaline Activated Fly Ash, they possess very similar mechanical properties. Research suggests that GPC exhibits the Tensile and Elastic Modulus characteristics of an engineered material that can be predicted by mathematically equations using the Compressive strength from the already established OPC standards.

Properties of Crumb Rubber

Between 2009-2010 an estimated 48 million EPU tyres reached their EOL in Australia. Of this only 16 per cent were domestically recycled with approximately 66 per cent were disposed either to landfill, stockpiled or illegally dumped (Department of the Environment, 2014). A typical tyre contains 70% recoverable rubber, 15% steel, 3% fibre and 12% inert filler material. Tyre Stewardship Australia (TSA) have developed a national tyre product stewardship scheme that aims to increase domestic tyre recycling, expand the market for tyre-derived products and reduce the number of end-of-life tyres ending up in landfill or illegal dumps. Crumb rubber is the result of a manufacturing process in which EOL tyres are shredded and 99 percent of the steel and fabric is removed. There are several different methods currently used for manufacturing crumb rubber including crackermill, granulator, micro-mill and cryogenic techniques. A combination of these techniques are used to produce the particle sizes required for aggregate usage.

Material Properties

Crumb rubber, as a partial replacement for fine aggregate, has a specific gravity of approximately 1.15 with particle sizes between 0.075mm-4.75mm. Granulated rubber can also be used as a replacement for coarse aggregate however, investigation in these material properties are beyond the scope of this research. Cohesion values ranged from 4.3 kPa to 11.5 kPa and it is non-reactive under normal environmental conditions. Crumb rubber can also exhibit high insulating properties. (Federal Highway Administration Research and Technology, 1997).

Behavioral research conducted with both OPC (Mendis, 2017) and GPC have concluded that a noticeable reduction in the workability is observed with an increase of rubber content. With OPC testing the workability is easily analysed using slump. Tests have shown that with 15% replacement of fine and coarse aggregate yields a 15% reduction in slump (Bravo, 2012) (Zeineddine Boudaoud, 2012). GPC does not flow in the same way as OPC due to the AAFA binder. This makes it difficult to establish a standardised behavioral reduction.

Preparing Crumb Rubber for use in Geopolymer Concrete

Interfacial bonding between crumb rubber aggregate and cement paste possess a problem due to the smooth surface of the rubber particles. Chemical pretreatment of rubber improves adherence and mechanical resistance compared with rubber concrete without pretreatment (Roman Chylík, 2017). Different methods of CR pre-treatment have been explore including water washing, NaOH pre-treatment, cement paste and mortar pre-coating (Khalid Battal Najim, 2013), acid etching, plasma and coupling agents (Segre & Joekes, 2000). Results indicated mortar pre-coating achieved good results in terms of fracture toughness and energy absorption. However, the NaOH aqueous solution also returned favourable results obtaining a high strength performance (D. Raghavan, 1998). This has promise for the inclusion into an AAFA based concrete as the NaOH is inherent in the mix and not an addition inclusion.

Properties of Crumb Rubber Geopolymer Concrete

Very limited research has been conducted to date using crumb rubber as an aggregate inclusion into geopolymer concrete particularly using NaOH pre-treated crumb rubber.

Mechanical Properties

Due to the lower density of CR (kg/m^3) when compared to the fine aggregate that its replacing (riverbed sand kg/m^3) the unit weight of the resulting CRGPC concrete is lower (Topçu, 2004) & (Clark, 1996). This reduction in material density will have a direct impact on the Elastic Modulus of the concrete as the Standards state that the E_c is directly proportional to the density of the concrete to the power of 1.5.

Experimental research has been conducted GPC replacing various percentages of aggregate with crumb rubber. Results showed that the compressive strength decreased as the rubber content increased however, the mixtures demonstrated a ductile failure. *Figure 6* (Ahmad Azrem Azmi, 2016) demonstrates the effects on the compressive strength of geopolymer concrete with crumb rubber additions. CRGPC decreases approximately 60% when 15% crumb rubber was added. Compressive strength of CRGPC mixtures are affected by the size, proportions, and surface texture of the crumb rubber particles, and mix composition of the bonding material. In addition, the failure of the samples also due to the crumb rubber being more elastically deformable than the matrix (Ahmad Azrem Azmi, 2016).

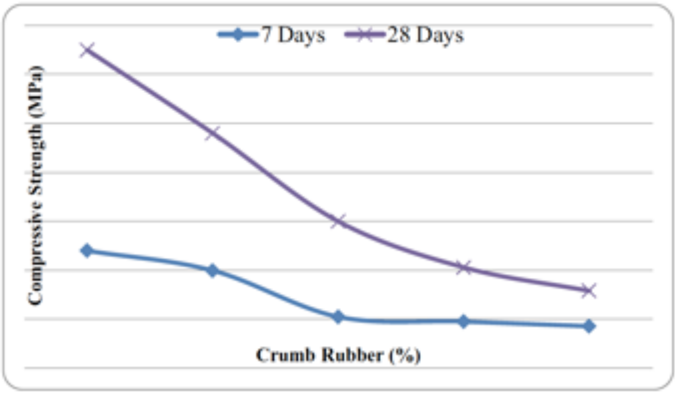


Figure 21. Compressive strength or CRGPC at 7 and 28 days

Research is headed towards affirming the predictable relationship predictable between the compressive and flexural strength as similar to Compressive strength, flexural strength also decreased as the rubber content increased.

Another effect of adding crumb rubber to concrete is the increase in deformability resulting from the reduction in the modulus of elasticity. The average CRC modulus of elasticity is 29.58 GPa where the same concrete without crumb rubber is 33.17 GPa (Gintautas SKRIPKIŪNAS, 2007).

Experimental testing under compressive and flexural loads has shown CRC is capable absorbing a large amount of energy (Li Z, 1998). Suitable applications for CR concrete could include applications where toughness is preferred over strength. This would include such as applications as driveways, noise barriers, crash barriers or sidewalks.

Summary

This literary review draws attention to the fact that minimal research studies have been carried out for investigation into characteristic material properties of CRGPC. However, multiple studies have been carried out on characteristic properties of CRC. No study has been carried out on the mechanical behaviour of similar compressive strength CRGPC. This literary review demonstrates a gap in the research regarding the characteristic properties of similar compressive strength CRGPC. Analysing the central aspects pertinent to this project, from the literature review, shows promise that the experimental research, into CRGPC with NaOH pre-treated crumb rubber, will return favourable results on the mechanical properties.