# AN INVESTIGATION INTO THE USE OF WEATHERED FLY ASH (WFA) AND COAL GASIFICATION ASH (CGA) AS PARTIAL REPLACEMENTS FOR PORTLAND CEMENT IN CONCRETE

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# TABLE OF CONTENTS

# DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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signature of candidate

24 ……………… day of July …………………………… year 2019 ………………

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# ABSTRACT

The cement industry has recognised the need to reduce the output of $CO_2$ emissions in the atmosphere. This investigation considers the use of alternative binders. Three supplementary cementitious materials (SCMs), namely, fly ash (FA), coal gasification ash (CGA), and weathered fly ash (WFA) were used to replace 10%, 15%, and 30% of Portland cement (PC) by mass. Each mix used water/binder (w/b) ratios of 0.50 and 0.60. 100% PC concrete was the primary control and FA concrete the secondary control. Samples were subjected to slump, compressive and tensile strength, durability and shrinkage tests. The compressive strength results of WFA blends at 28-days of testing were observed to be equal to or greater than those of FA blends. At 56-days the compressive strength results of WFA blends measured below those of 28-days. The compressive strength results of 15% CGA blend at 28-days of testing was equal to that of 15% FA with 0.50 w/b and greater than that of 15% FA with 0.60 w/b ratio. The 56-days strength of 30% CGA-0.50 and 30% CGA-0.60 were greater than the corresponding 30% FA blends at 28-days of testing. Indicating an increase in strength with age for CGA blends. Due to the loss of compressive strength at 56-days for WFA, CGA was concluded to be the Sasol ash with the higher potential to be used as a partial replacement of PC in concrete for strength purposes. The durability index tests conducted had varying overall results, CGA blends were less permeable to oxygen, FA blends had the lowest absorption rates and WFA blends were the most resistant to chloride ingress. In conclusion, from the observed results, CGA and WFA can be used as partial replacements of PC in concrete, but further research is required. The research into WFA and CGA as supplementary cementitious materials will assist in gaining knowledge on their impact on the concrete characteristics to allow for greater exploitation.

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# TABLE OF FIGURES

# LIST OF TABLES

# LIST OF SYMBOLS

k = coefficient of permeability (m/s)

$\omega$ = molecular mass of permeating air (kg/mol)

V = volume of the pressure cylinder ($m^3$)

g = acceleration due to gravity ($m/s^2$)

d = specimen thickness (m)

R = universal gas constant (Nm/Kmol)

A = cross-sectional area of specimen (m2)

$\delta$ = absolute temperature (K)

t = time (s)

$P_0$ = pressure at the start of test (kPa)

P = pressure at time t (kPa)

F = slope of the best fit line (g/√hr)

d = average specimen thickness to the nearest 0.02 mm (mm)

$M_{SV}$ = vacuum saturated mass to the nearest 0.01 g of the specimen (g)

$M_{S0}$ = mass to the nearest 0.01 g of the specimen at the initial time $t_0$ (g)

$\delta$ = chloride conductivity of the specimen (mS/cm)

i = electrical current (mA)

d = average thickness of specimen (cm)

V = voltage (V)

A = cross sectional area of the specimen ($cm^2$)

$\varepsilon$ = drying shrinkage strain

$n$ = number of measurements

$L_n$ = current measurement (μm)

$L_{n-1}$ = previous measurement (μm)

$L_0$ = initial length of specimen

$\bar{X}$ = sample average

$n$= size of random sample

s= sample standard deviation

df = degrees of freedom

t = T value obtained from the t-distribution tables, 95% confidence interval the corresponding

t value; degrees of freedom (n-1)=2 was 4.303, (n-1)=3 was 3.182, (n-1)=14 was 2.145

$x_i$= individual test results

w/b ratio = water/binder ratio

# NOMENCLATURE

PC – Portland cement

CGA – coal gasification ash

WFA – weathered fly ash

Sasol ashes – WFA and CGA

FA – fly ash

SCM – Supplementary cementitious materials (SCM)

SCM, WFA, CGA, FA – Supplementary cementitious materials

Cement – PC, WFA, CGA and FA

FBDB – fixed bed dry bottom

$CO_2$ – Carbon dioxide

# CHAPTER 1 – INTRODUCTION

## 1.1 Background

Concrete is a commonly-used construction material, known for its positive strength and durability characteristics (Grieve, 2009; Ballim, et al., 2009). The global cement industry has recognised the necessity to reduce carbon dioxide ($CO_2$) emissions (Millera, et al., 2017; Kajaste & Hurme, 2016). The production of cement is responsible for approximately seven per cent of the total global $CO_2$ emissions (Casper, 2010; International Federation for Structural Concrete, 2012; Chemistry World, 2008). For every tonne of Portland cement (PC) produced, approximately one tonne of $CO_2$ is emitted (Islam & Islam, 2010). Increasing focus has been on researching and developing methods to limit the amount of $CO_2$ emitted (Silfwerbrand, 2012), such as:

- Effective production of cement and alternative fuels
- Use of alternative binders
- Optimising cement mixes
- Optimising concrete cross-sections
- Optimising reinforcement for reinforced concrete designs
- Maintenance of concrete structure during the serviceability state
- Prolonging the service life of concrete structures
- Reuse and recycling of concrete

Durability is the property of concrete, which has the ability to withstand weathering action, chemical attack, abrasion or any other process of deterioration (Devi, 2018). The durability of concrete is evident in its ability to withstand the exposure environment over the design life, without undue loss of serviceability or need for major repair (Ballim, et al., 2009).

Portland cement (PC) is a dominant binder used in the cement and construction industry (Juenger, et al., 2011). No other binder has been as extensively marketed and implemented as PC (Practical Action, n.d.). To reduce the production and demand of PC, alternative binders – referred to as supplementary cementitious materials in this investigation, were used. Supplementary cementitious materials have cementing properties when used with PC and water (Grieve, 1991). Three common supplementary cementitious materials are available: fly ash (FA), ground granulated blast-furnace slag (GGBS) and silica fume (SF). FA is collected from the exhaust flues of furnaces burning finely ground coal in power stations. GGBS is a by-product of the iron-making process and SF is the condensed vapour by-product of the ferro-silicon smelting process.

FA is pozzolanic, which means that it is able to develop strength when it reacts with lime (e.g. lime liberated by hydrating Portland cement) in the presence of moisture, hence its main value as a supplementary cementitious material (Kruger, 2003; Kruger, 1987). When it encounters lime and water a chemical reaction takes place to produce calcium silicate hydrate (C-S-H) (Owens, 2009). PC and FA have a similar chemical composition (Kruger, 1987.; Kruger, 2003; Roy, et al., 2012). Due to the similarity, FA has been used to alter the characteristics of PC, reducing permeability, increasing strength and improving workability (Grieve, 2009).

SASOL, a South African company producing liquid fuels and petrochemicals, produces weathered fly ash (WFA) and coal gasification ash (CGA) as waste by-products (Dyk, et al., n.d.; Mahlaba, 2006). CGA is coarse dark grey ash and WFA is fine light grey ash (Mahlaba, et al., 2011). SASOL is interested in determining positive utilizations of the Sasol ashes (WFA and CGA) (Matjie, et al., 2005). There are two plants producing a total of 7.5 million tons of Sasol ashes annually, one is in Secunda, Mpumalanga and the other in Sasolburg, Free State in South Africa (Matjie, et al., 2005). Mahlaba (2006) observed a similarity between the chemical composition of Sasol ashes and FA. Leading to the assumption that WFA and CGA could be potential supplementary cementitious materials, replacing a portion of PC in concrete, Figure 1 and Figure 2 shows pictures of the CGA, WFA and FA.

**(a)** Coal gasification ash (CGA) **(b)** CGA after pulverization

Figure 1: Photographs of the supplementary cementitious material CGA

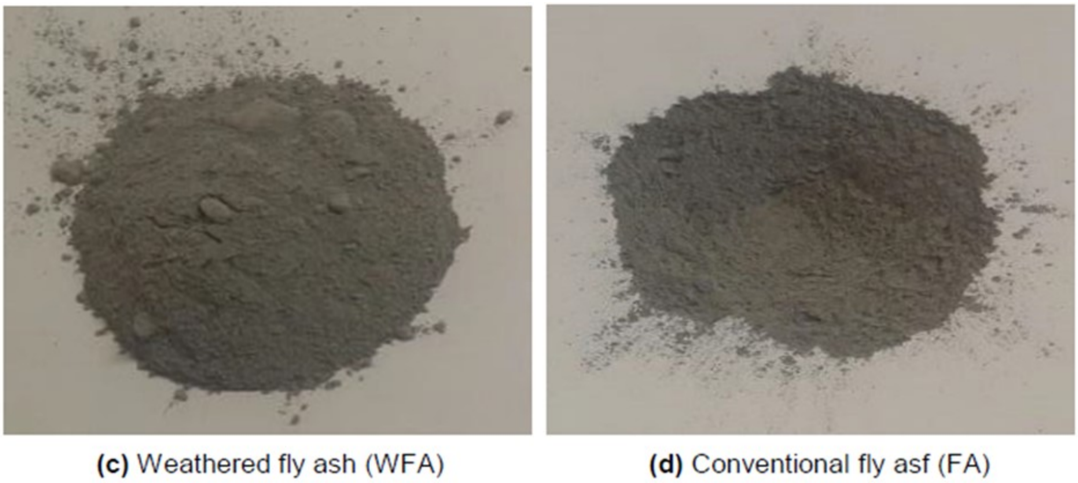
**(c)** Weathered fly ash (WFA) **(d)** Conventional fly asf (FA)

Figure 2: Photographs of the supplementary cementitious materials WFA and FA

## 1.2 Motivation and research significance

Approximately half of the carbon dioxide ($CO_2$) emitted by the cement industry originates from the fuel, and the other half from the calcinations that will convert raw materials into clinker (Caruso, 2006). $CO_2$ is a greenhouse gas which functions to contain heat with minimum loss, warming up the earth (Casper, 2010). The gradual consistent increase of $CO_2$ concentration has raised environmental concerns. This has led to what scientists have termed "climate change". The theory of climate change is supported by the observation of varying weather conditions from the recurrent way when considering long time scale (UNEP; UNESCO; WHO, 2011).

Even though PC is extensively used and has been proven to contribute positively to the strength and durability of concrete, it has certain limitations (Owens, 2009; Perrie, 2009; Portland Cement Association, 2013). Portland cement may result in durability problems for concrete constructed in aggressive environments (e.g. with high sulphate concentrations), thus it may not be the ideal material for all types of construction (Juenger, et al., 2011).

The utilisation of supplementary cementitious materials (SCM) has been found as a suitable alternative to reduce $CO_2$ emissions from PC production and improve the durability of concrete (Devi, 2018; Grieve, 1991; Zode, 1999). Fly ash (FA) is a common SCM and has been used for decades in cement applications (Kruger, 1987; Kruger, 2003). FA replaces clinker in cement blends, which reduces the consumption of resources and energy and at the same time, avoiding the environmental burden associated with clinker production (Vargas & Halog, 2015).

Currently, a small percentage of the 7.5 million tons of WFA and CGA is recycled (Matjie, et al., 2005). Tens of thousand tons of coarse and fine ash is hauled away each month by contractors (Reynolds, n.d.). In the Vaal triangle area there is a well-established brick manufacturing market where between 2 to 3 million ash cement bricks are made a day, most of which contain screened CGA from the Sasolburg site (Matjie, et al., 2005). Close to the Secunda site, 6500 hollow and stock bricks are produced per week from the Sasol ashes (Yende, 2016). In order to:

- reduce the rate of annual disposal
- minimise the potential of serious and acute environmental problems
- free-up habitable land from being used as dumping sites
- intercept surface water and ground water pollution

the consumption of Sasol ashes needs to increase (Mahlaba, 2006; Matjie, et al., 2005)

CGA and WFA are composed of chemical compounds known to contribute to the production of cementitious compounds products in concrete (Mahlaba, 2006; Mahlaba, et al., 2011).

## 1.3 Problem Statement

Matjie, et al. (2005) has reported that the use of CGA as a supplementary cementitious material has the potential to be a large-scale utilisation opportunity. Currently not enough is known about the effect of CGA and WFA on concrete. Understanding the properties of the Sasol ashes as partial replacements will assist in determining their potential use as supplementary cementitious materials. It is on these grounds that the following aims and objectives are set for this investigation.

## 1.4 Aim and objectives

The aim of this investigation is to determine the potential of using WFA and CGA as partial replacements for PC in concrete.

The objectives of this investigation were as follows;

- Assess the chemical composition of FA, WFA and CGA
- Determine the effect of w/b ratios, 0.50 and 0.60, on the workability, drying shrinkage, strength and durability of CGA and WFA concrete in comparison to 100% PC concrete.
- Analyse the workability, drying shrinkage, strength and durability outcomes of CGA and WFA concrete when they replace 10, 15 and 30% of PC by mass.

- Assess all test results for WFA and CGA blends to those of comparable FA blends
- Synthesise information to provide an understanding of the potential use of WFA and CGA as supplementary cementitious materials

## 1.5 Scope and limitations

The scope of this investigation is limited to the following constraints:

- Portland cement, commercial fly ash, weathered fly ash and coal gasification ash as cementitious material
- Two w/b ratios of 0.50 and 0.60
- Three PC replacement percentages of 10%, 15% and 30%
- Workability, drying shrinkage, strength and durability testing

## 1.6 Structure of the dissertation

This investigation report is divided into five chapters as follows:
Chapter one – is the introduction, consisting of the background of the investigation, the problem statement, motivation and significance of research, scope and limitations, and aims and objectives.

Chapter two – presents the literature review on the partial replacement of PC, Sasol ashes comparison to commercial fly ash (FA), the environmental impact of PC and FA, and strength and durability properties of blended cement.

Chapter three – presents a detailed methodology on the preparation of material, experimentation, analysis, and experimental variables and constants.

Chapter four – discusses the results observed from the slump, compressive strength, tensile splitting strength, drying shrinkage and durability index (oxygen permeability, water sorptivity and chloride conductivity) tests. The results are accompanied by analyses and discussion.

Chapter five – concludes the dissertation by giving the conclusions based on the investigation findings and recommendations for future study.

# CHAPTER 2 – LITERATURE REVIEW

## 2.1 Introduction

This chapter will demonstrate the knowledge and findings uncovered through the survey of literature for the investigation into the use of Sasol ashes as partial replacement of PC in concrete. The chapter commences with the concept of partial replacement of PC discussing the history of cement and partial replacement technology. The various types of supplementary cementitious materials are introduced and a comparison of Sasol ashes to FA is made. The strength and durability properties of blended cement compared to 100% PC are also discussed.

## 2.2 Partial replacement of Portland Cement

### 2.2.1 History of Portland Cement

Portland cement is a hydraulic cement that sets and hardens by reacting with water (Kosmatka, et al., 2002). It is used as a basis of cementitious materials, generally defined as a binder, glue or adhesive (Grieve, 2009). The term "Portland" in Portland cement originated in 1824, as the cement blend produced concrete that resembled the colour of the natural limestone quarried on the Isle of Portland in the English Channel (Rinker Materials, 2010). PC is the most common cement derived from the calcining of clay, sand and limestone, which are all-natural resources (Ohanyere, 2013).

Early builders used clay to bind stones together into a solid structure for shelter and protection. Buckley (2001) (as cited in Ohanyere, 2013) found that the Assyrians and Babylonians put up structures with a clayey material. The oldest concrete, consisting of a lime concrete made from burning limestone to produce quicklime, which when mixed with water and stone, hardened to form concrete was discovered to date as far back to around 7000 BC. This concrete was found in 1985 when a concrete floor was uncovered during the construction of a road at Yiftah El in Galilee, Israel (Kosmatka, et al., 2002).

In the 1890s, the first South Africa cement producer was established in Pretoria as the "*De Eerste Cement Fabrieken Reperkt*" now known as "*Pretoria Portland Cement Company Limited*" after a name change in 1908 (PPC, 2017). It was established to counter the exorbitant delivery cost of cement imported from Europe (PPC, 2010). Today, many South African companies produce cement, including Lafarge, AfriSam, National Portland Cement (NPC), Sephaku and PPC.

### 2.2.2 Production of Portland Cement

There are two basic methods to produce cement; the wet, and dry method. In 1958, Pretoria Portland Cement (PPC) slurry operation converted from the wet-process to the dry mix system (PPC, 2010). The wet process carries out the grinding and blending operations with the materials mixed with water in a slurry form, whilst the dry process carries out grinding and blending with dry materials (Kosmatka, et al., 2002). The dry process is considered more efficient and cost effective (PPC, 2010). It is less energy intensive, more cost effective (it does not require evaporation of the wet slurry before calcination) and uses less water (Cochez & Nijs, 2010).

Portland cement is produced through the process of mixing raw material, burning at around 1500°C, grinding to fine powder, storage and packaging. The raw materials used are, lime, silica, alumina and iron (Cochez & Nijs, 2010; Grieve, 2009; Kosmatka, et al., 2002). Lime (CaO) is a man-made product derived from limestone ($CaCO_3$). $CaCO_3$ is heated at temperatures between 800 to 1000°C in a rotating kiln to produce CaO (Grieve, 2009). This reaction produces $CO_2$ as a by product. Silica ($SiO_2$ – silicon dioxide), alumina ($Al_2O_3$ – Aluminium oxide) and iron ($Fe_2O_3$ – ferric oxide) are natually occuring and found in clays or shale.

PC clinker is produced from the continued heating of the raw material to a temperature of about 1400°C. The clinker is then mixed and milled with gypsum which retards the setting of the cement. A typical chemical composition of South African PC is indicated in Table 1.

Table 1: Typical chemical composition of Portland cement (Grieve, 2009)

| **Oxides** | **% by mass in PC** |
|---|---|
| CaO | 63 – 69 |
| $SiO_2$ | 19 – 24 |
| $Al_2O_3$ | 4 – 7 |
| $Fe_2O_3$ | 1 – 6 |
| MgO | 0.5 – 3.6 |
| $Na_2O + 0.658K_2O$ | 0.2 – 0.8 |

The four raw materials contribute four oxides (CaO, $SiO_2$, $Al_2O_3$, $Fe_2O_3$) to the manufacturing of PC (Kosmatka, et al., 2002). The raw material also consists of magnesia and alkalis which become part of the clinker (Grieve, 2009). For a cement produced from lime (CaO) and silica ($SiO_2$)to be identified as Portland cement, lime and silica should occupy about 60 – 73% of the clinker (Grieve, 2009). The oxides contribute to the formation of the cement compounds, one of which being tricalcium silicate ($3CaO.SiO_2$), responsible for most of the early strength (first 7 days). A PC clinker contains a large proportion of tricalcium silicate ($C_3S$) and only a negligible amount of free lime (CaO) (Grieve, 2009) (Kosmatka, et al., 2008).

### 2.2.3 Types of cement

There are 5 common types of common cements according to SANS 50197 – 1. They are; CEM I, CEM II, CEM III, CEM IV and CEM V. CEM I is composed of 95 – 100% clinker and 0 – 5% minor additional constituents (mostly limestone). The other four types can have a clinker range between 20 to 94%. Rinker (2010) and Ohanyere (2013) provided a brief explanation of each common cement in terms of suitable application;

- CEM I is considered “pure PC”. It is used for general purposes with no anticipated sulfate or chloride attack on the concrete structure. Its uses include pavements and sidewalks, reinforced concrete buildings, bridges, railway structures, tanks, reservoirs, culverts, sewers, water pipes and masonry units.

- CEM II contains varying additions of secondary materials, i.e. fly ash, pozzolana, slag, silica fume, or limestone blended cements. This is suitable for structures exposed to soils or water containing sulfate ions at a moderate level. It has a low tricalcium aluminate ($C_3A$) ($\leq 8\%$) content. $C_3A$ is a cementing compound that contributes slightly to early strength development of concrete. The rate of hydration is less than CEM I and can be used in massive structures and in warm temperatures.

- CEM III is blast furnace cement ground more finely to have slightly more $C_3S$ which results in high early strength, witnessed within a week or less. The cement is suitable for rapid construction and cold weather concrete. CEM I can be manipulated to achieve early strength but CEM III gives more economical and satisfactory results.

- CEM IV pozzolanic cement, according to ASTM C150 and AASHTO M 85 (as cited by Kosmatka, et al. (2002) and Rinker Materials, (2010)), is mentioned as consisting of three types of air-entraining PC (types IA, IIA and IIIA), corresponding in composition respectively to ASTM Types I, II and III, except that small quantities of air-entraining material are interground with the clinker during manufacturing. Ohanyere, (2013) and Thomas & Jennings (n.d.) make no mention of air-entrained PC. They describe the cement as slow reacting due to the low content of $C_3S$ and $C_3A$ and suitable for massive structures.

- CEM V composite cement is high sulfate resisting due to the very low proportion of $C_3A$ (<5%). It is suited to concrete structures that may be exposed to severe sulfate action principally where soils or groundwater have a high sulfate content.

### 2.2.4 Blended cements

Supplementary cementitious materials are finely divided material which form a paste to supplement PC paste. They assist PC to gain additional physical, chemical and/or mechanical properties. The known and commonly used supplementary cementitious materials are fly ash, slag, silica fume and limestone (Owens, 2009). In recent times blended cements are being used even more than “pure PC”. CEM II to CEM V are blended cements with varying proportions of PC replacement and types of supplementary cementitious materials.

Blended cements have become popular due to the technical and environmental benefits that have been observed. Listed below are the general observations, not highlighting any specific supplementary cementitious material (Grieve, 2009; Kruger, 1987; Kosmatka, et al., 2002).

a. Technical advantages

- Reduced water demand
- Reduced water/binder ratio.
- Improved workability for the same water content.
- Decreased permeability of concrete.
- Increased durability as a result of hydraulic properties creating secondary crystal growth thereby increasing concrete density.

b. Environmental advantages

- Energy saving: Blended cements are obtained by adding mineral admixtures with clinker. The energy, which would have otherwise been utilised for production of CEM I, is thus saved.
- Conservation of natural resources: The used mineral admixtures are the by-products of power generation and steel plants. By using these products, we are conserving the natural resources like limestone, clay and silica, etc.
- Pollution control: By reducing the production of clinker, pollution is also controlled as cement is an energy-intensive product

### 2.2.4.1 Supplementary cementitious materials

There are three types of supplementary cementitious materials commonly used in South Africa namely, fly ash (FA), granulated blast furnace slag (GBFS) and condensed silica fume (CSF). They are all by-products of existing processes.

*Fly Ash*

Fly Ash (FA) is an industrial by-product during the combustion of coal in thermal power plants (TPPs) (Zode, 1999). It is categorised into fine and coarse material. The fine material is collected by electrostatic precipitators or bag filters from the flue gases of furnaces fired with pulverised coal (Grieve, 2009), or other suitable technologies (Zode, 1999).

Fly Ash has been defined as follows:

"A siliceous and aluminous material that in itself possesses little to no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with $Ca(OH)_2$ at ordinary temperatures to form compounds possessing cementitious properties" (Landman, 2003)

and

"The cementitious compound is calcium silicate hydrate, produced after the hydration process that produces free lime" (Grieve, 2009).

The first investigation into the use of South African FA as a supplementary cementitious material was done by the National Building Research Institute (NBRI) of the CSIR in 1955 for SASOL and ESKOM (Kruger, 1987). Table 2 shows a typical chemical composition of South African FA.

Table 2: Typical chemical composition of fly ash (Grieve, 2009)

| **Oxides** | **% by mass in PC** |
|---|---|
| CaO | 4 – 7 |
| $SiO_2$ | 48 – 55 |
| $Al_2O_3$ | 28 – 34 |
| $Fe_2O_3$ | 2 – 4 |
| MgO | 1 – 2 |
| $Na_2O + 0.658K_2O$ | 1 – 2 |

FA as a pozzolan is used as a percentage of PC mass. Commercially, not more than 30% is made available for building and construction projects. Greater than 50% is considered high volume fly ash and requires better handling and curing (Mehta, 2004). PC with 15-20% FA by mass exhibits positive effects on the workability and cost, whilst 25-35% FA by mass improves the durability to sulphate attack, alkali-silica expansion and thermal cracking (Mehta, 2004).

*Ground Granulated Blast-Furnace Slag*

Ground granulated blast-furnace slag (GGBS) is a recognised supplementary cementitious material, it is a by-product of the blast furnace process which is used to produce iron (Grieve, 2009). No two GGBSs are the same from different sources, but they have been proved to consist mainly of silica and alumina, derived from the iron ore, and lime or dolomitic lime added as a fluxing agent (Grieve, 2009).

There are two methods of cooling blast-furnace slag, slowly by air cooling and rapidly by quenching with water. If the slag is cooled slowly, it is rendered useless in producing cementing compounds. Slow cooling results in a crystalline state that is insufficiently reactive to function effectively as a supplementary cementitious material. The rapid cooling leads the slag to assume a glassy or amorphous state (rough and angular-shaped) which is reactive in producing cement compounds (Kosmatka, et al., 2002).

When GGBS is quenched it leads to the development of granules, which are then milled to a fine powder less than 45 microns (Grieve, 2009). The hydration products of GGBS are similar to those of PC except that no free lime is liberated (Grieve, 2009). Table 3 shows GGBS typical chemical composition of GGBS.

Table 3: Typical chemical composition of South African ground granulated blast-furnace slag (Grieve, 2009)

| Oxide | % by mass in GGBS |
|---|---|
| $SiO_2$ | 34 - 40 |
| CaO | 32 - 37 |
| $Al_2O_3$ | 11 - 16 |
| FeO | 10 - 13 |
| MgO | 0.3 - 0.6 |
| MnO | 0.7 - 12 |
| $K_2O$ | 0.8 - 1.3 |
| S | 1.0 - 1.7 |
| $TiO_2$ | 0.7 – 1.4 |

The chemical composition of GGBS is similar to PC, with a high lime content. GGBS has a large proportion of lime, enabling it to be more cementitious than pozzolanic (Grieve, 2009). On its own, GGBS hardens very slowly and, for use in concrete it needs to be activated by combining it with PC (Suresh & Nagaraju, 2015).

GGBS offers greater resistance to chemical attack making it suitable for marine works (Grieve, 2009). The 45 microns particle fineness confers resistance to bleeding in the fresh state and lower permeability when hardened. The glassy surface of the slag may give a slightly reduced water requirement even though it does not have the favourable spherical particle shape of fly ash (Grieve, 2009). GGBS generates heat more slowly and so produces distinctly lower peak temperatures in most applications, reducing the chances of thermal cracking (Grieve, 2009). Although it has worthwhile advantages, there are some disadvantages such as the lower initial strength and higher dry shrinkage (Eguchi, et al., 2013).

### *Condensed Silica Fume*

Condensed silica fume (CSF) is a by-product of the ferrosilicon smelting process (Grieve, 2009). This by-product is a result of the reduction of high-purity quartz with coal in an electric arc furnace in the manufacture of silicon or ferrosilicon alloy (Kosmatka, et al., 2002). CSF is the condensed vapour from the process (Grieve, 2009). When it is cooled it condenses and is collected in huge cloth bags. The condensed silica fume is then processed to remove impurities and to control particle size. CSF is essentially silicon dioxide (usually more than 85%) in a non-crystalline (amorphous) form. It is extremely fine with particles less than 1 μm in diameter and with an average diameter of about 0.1 μm, about 100 times smaller than average Portland cement particles (Kosmatka, et al., 2002).

Due to this fineness, particles are strongly attracted to each other and cannot slide or roll over each other to achieve a dense packing and consequently is difficult to handle and transport (Grieve, 2009). In order to make the material more manageable, CSF is “densified” by means of electrostatic forces that cause particles to agglomerate into small pellets about 0,5 mm in diameter (Grieve, 2009).

CSF is a pozzolan (Kosmatka, et al., 2002 and Grieve, 2009). It forms cementing compounds in water by reacting with calcium hydroxide and not by hydration – i.e. reaction with water – as do PC and GGBS (Grieve, 2009). Table 4 shows the typical chemical composition of South African CSF.

Table 4: Typical chemical composition of Condensed Silica Fume (Grieve, 2009)

| Oxide | % by mass in CSF |
|---|---|
| $SiO_2$ | 92 - 96 |
| $Al_2O_3$ | 1.0 - 1.5 |
| $Fe_2O_3$ | 1.0 - 1.6 |
| CaO | 0.3 - 0.6 |
| MgO | 0.6 - 0.8 |
| $K_2O$ | 1.2 - 2.0 |
| $H_2O$ | 0.4 - 0.8 |

Both FA (Table 2) and CSF have much lower lime composition compared to that of GGBS (Table 3) and PC. The cementing compounds formed by CSF as a pozzolan are similar to those formed by the hydration of PC (Grieve, 2009). The specific surface area (fineness) of CSF ranges from 13 000 to 30 000 $m^2/kg$ (Siddique & Khan, 2011) Unlike FA, and due to the super fineness of CSF, it is highly reactive, reacting with free lime very effectively. Silica fume concrete provides a previously unattainable level of low permeability in addition to the chemical conversion of the most vulnerable calcium hydroxide into durable calcium silicates (Kosmatka, et al., 2002). In many instances, CSF permits the attainment of 28-days strength in excess of 100 MPa, when 80 MPa might be difficult to attain without it.

Silica fume is sold in powder form. It is used in amounts between 5% and 10% by mass of the total cementitious material, because it is relatively expensive. It is used in applications where a high degree of impermeability is needed and in high strength concrete. Due to it increasing impermeability in concrete, it improves resistance to chloride and sulphate attack (Owens, 2009).

There is disagreement as to whether the use of silica fume increases water demand or not (Kosmatka, et al., 2002). This decrease may depend on the particular size of the material but also on how it is used. To be fully effective it must be dispersed so that it occupies spaces between cement grains and must not remain in clumps of fume particles.

## 2.3 Sasol ashes

The South African construction sector mainly uses FA from coal power stations, and GGBS. The FA has been researched and developed as a supplementary cementitious material (Kruger, 1987.; Kruger, 2003; Roy, et al., 2012). The hypothesis of this investigation is, since Sasol ashes have a similar chemical composition to FA, they would exhibit similar performance characteristics.

Coal gasification ash (CGA) is a by-product of the SASOL-LURGI fixed bed dry bottom (FBDB) gasification process producing crude gas which is purified and then used to produce liquid fuels and petrochemicals (Mahlaba, 2006; Venter, 2005). Weathered fly ash (WFA) is a combination of approximately 83% power station fly ash and 17% both gasification ash and bottom ash fines (<250 µm) (Mahlaba, et al., 2011). Table 5 details the oxides associated with the production of cementing compounds observed by Mahlaba (2006) and Matjie, et al. (2011) and their proportions.

Table 5: Chemical composition of a) coal gasification ash (Matjie, et al., 2011) and b) weathered fly ash (Mahlaba, et al., 2011)

| **Oxide** | a) % by mass in CGA | b) % by mass in WFA |
|---|---|---|
| $SiO_2$ | 43.5 – 55 | 43.1 - 43.11 |
| $Al_2O_3$ | 23.2 – 29.9 | 26.01 – 30.89 |
| $Fe_2O_3$ | 6.2 – 8.5 | 8.46 – 11.05 |
| CaO | 2 – 5.5 | 1.91 – 16.62 |
| MgO | 1.6 – 3.3 | 1.5 – 2.33 |

Since WFA has a greater proportion of lime than CGA, it can be assumed that WFA would produce more cementing compounds, tricalcium silicate ( $C_3S$), dicalcium silicate ($C_2S$) and tricalcium aluminate ( $C_3A$), than CGA. FA and WFA have almost similar oxide proportions, the expectation is for WFA to behave similar to FA.

The first research into Sasol ashes being used as supplementary cementitious materials was done in 1955. The results were inconclusive, this was assumed to be due to the coarseness of the ash (Kruger, 1987). No further work on Sasol ashes being used as supplementary cementitious materials was identified by the author. Mahlaba (2006) carried out an X-ray fluorescence (XRF) test on CGA and WFA, oxides which contribute to the production of cementitious compounds were observed, resulting in the recommendation for them to be considered as supplementary cementitious materials.

### 2.3.1 Production process resulting in the CGA and WFA by-products and WFA

SASOL was established in 1950 in Sasolburg to convert low grade coal into petroleum products and chemical feed stocks. The first liquid fuels and chemicals produced were in 1955 (Sasol, 2000). SASOL uses the SASOL-LURGI fixed-bed dry bottom (FBDB) process to produce synthetic gas which is then converted to more than 200 fuel and chemical products (Dyk, et al., n.d.).

The SASOL-LURGI FBDB gasification process is an indirect gasification process with temperatures limited to less than 900 – 1000°C, preventing slagging and related solids problems at elevated temperatures (SynGas Technology Inc, 2018). This method uses pipes to transfer temperature, impacted by the temperature of the hot gas within the pipe supplying the heat and the surface area of the hot surface.

Coal gasification ash is produced from the SASOL-LURGI FBDB gasification process (Venter, 2005). Low grade coal fills the gasifier and is heated up using steam from the thermal power station and oxygen (Mahlaba, 2006). Figure 3 illustrates the SASOL-LURGI gasifier with directional arrows indicating inputs and outputs. Less dense ash rises and sticks to the walls of the gasifier or carried out in gas for to be filtered, is referred to a CGA, the heavier ash settles at the bottom, referred to as bottom ash.

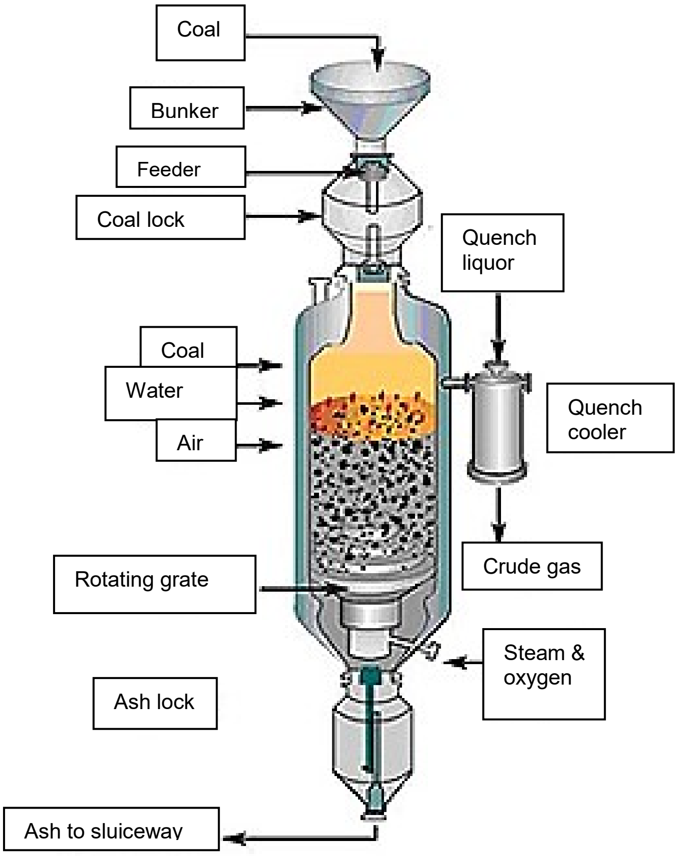

Figure 3: Illustration of SASOL-LURGI coal gasifier (Venter, 2005)

Coal is supplied to the SASOL-LURGI FBDB gasification process. Gasification can be defined as a conversion of coal through interaction with air and steam at high temperature (>700 ° C) to syngas ($H_2$ and CO) which can be used as a source of energy or synthesis of chemicals and liquid fuels (Collot, 2005 and van Dyk et al., 2005). The advantages of gasification process include high efficiency and low emissions of $NO_x$ and $SO_2$ to the atmosphere (Harris et al., 2004).

The steam injected is from a SASOL power station used to generate its own electricity and subsequently steam for the gasification process to produce crude gas. The power plant uses low grade coal provided by SASOL Mining, producing coarse fly ash (Matjie, et al., 2005). A simplified illustration of the SASOL-LURGI FBDB gasification process is illustrated in Figure 4.

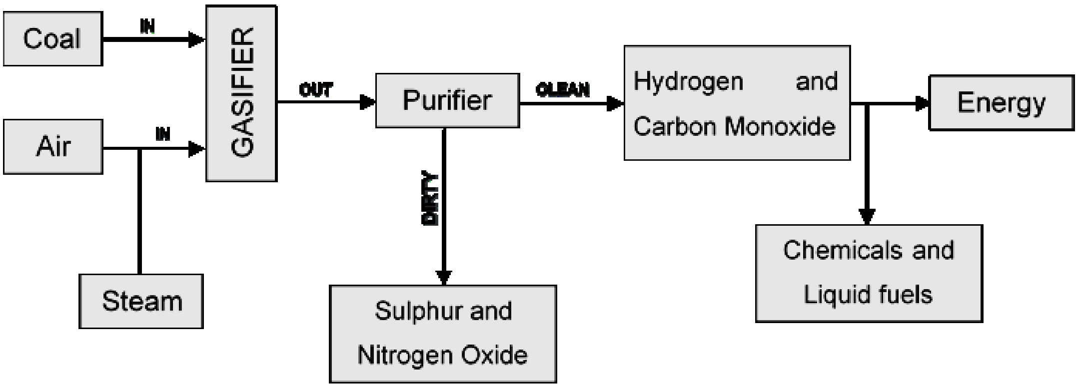

Figure 4: Simplified SASOL-LURGI FBDB gasification process (Venter, 2005; Dyk, et al., n.d.: Mahlaba, 2006)

At the coal power station, SASOL apportions the steam for the coal gasification process and the production of electricity. Producing electricity from coal starts when the coal is pulverised in huge mills into a fine powder before it is blown into huge kettles, called boilers. Due to the heat in the boiler, the coal particles combust and burn to generate heat to turn water into steam. The steam from the boilers is used to turn the blades of a giant fan or propeller, called a turbine. The turbine turns a coil made of copper wire (the rotor) inside a magnet (the stator). Together they make up the generator. The generator produces an electric current, which is sent for consumption via power lines. Figure 5 illustrates the electricity generation process. The fly ash fines are collected from the huge boilers by electrostatic precipitators or other particle filtration equipment before the flue gases reach the chimneys (Senapati, 2011). The 83% of the coal power station fines are mixed with 17% of those from the gasification process to be dumped either in slurry form or dry form at fly ash waste heaps (Matjie, et al., 2005).

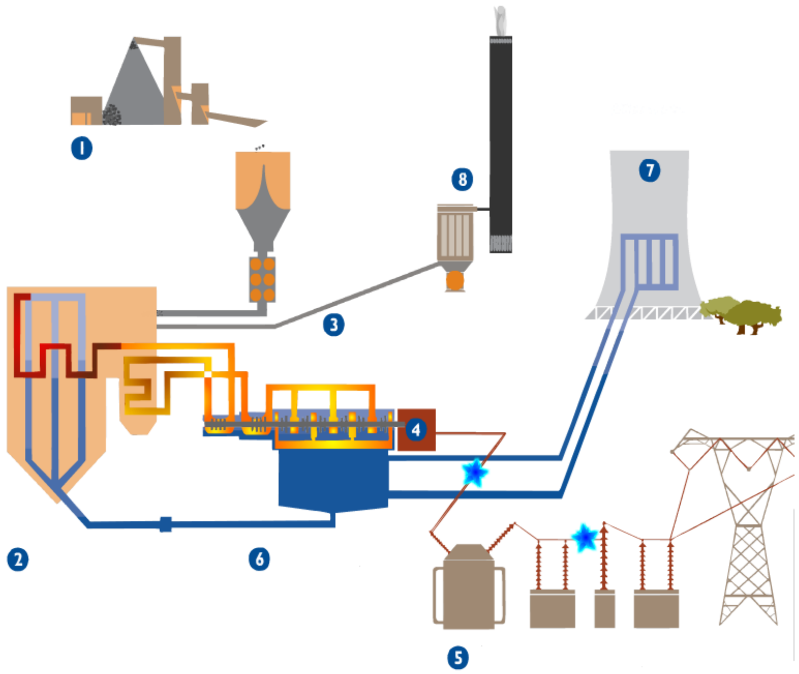

Figure 5: Coal power station electricity production process (Anon., 2019)

Approximately 150 000 barrels per day of liquid fuels and petrochemicals are produced from coal (Dyk, et al., n.d.). From the gasification and combustion process, an estimated 1 200 tons of ash is produced per hour (Mahlaba, 2006). A 12-hour operation shift translates to 14 400 tons of ash produced mostly destined for disposal.

### 2.3.2 Chemical / Mineralogical composition of weathered fly ash and coal gasification ash

The composition of $CaO_2$, $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ affects the glass phase of concrete (Keyte, 2009; Katherine L. Aughenbaugh, 2016). The glass phase also known as amorphous and is known to be reactive in producing cementing compounds (Kosmatka, et al., 2002). There are multiple glassy phases within a given fly ash (Hemmings & Berry, 1987). Katherine L. Aughenbaugh (2016) identified four glassy phase compositions in different fly ashes, aluminosilicate glasses, calcium aluminosilicate glasses, a mixed glass, and, in one case, a high iron glass. WFA and CGA in Table 5 are rich in alumina and silicate, CGA has a proportion of $SiO_2$ than WFA, whilst WFA has a higher proportion of $Al_2O_3$. Taking into consideration $Fe_2O_3$ and $CaO_2$, WFA would produce slightly more cementing compounds.

### 2.3.3 Physical properties of weathered fly ash and coal gasification ash

The image shown in Figure 6 is of CGA, it was obtained during the scanning electron microscope (SEM) analysis at SASOL internal laboratory by Mahlaba, 2006.

Figure 6: Image of magnified coal gasification ash (Mahlaba, 2006)

Mahlaba (2006) reported that the particles were mainly irregular in shape, including the agglomerated particles from finer particles. The morphology is quite different from that of fly ash (Font et al., 2005), which is mostly spherical. A sample of WFA was also analysed using SEM at Sasol Research & Development, the micrograph is shown in Figure 7.

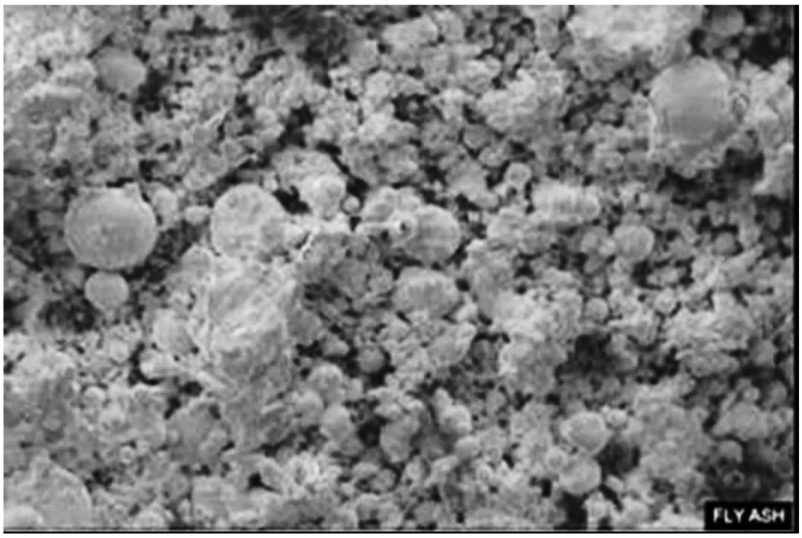

Figure 7: Image of magnified weathered fly ash (Mahlaba, 2006)

The majority of the particles are spherical in shape although there are some particles that seem to have agglomerated into irregular particles (Mahlaba, 2006). Table 6 provides a brief comparison of the Sasol ashes physical and chemical characteristics. CGA has a greater percentage of glass phase than WFA, but the lime content range of WFA is large than that of CGA. Lime contribute to the strength of concrete and the glass phase indicates the reactivity of fly ash to producing cementing compounds (Keyte, 2009; Katherine L. Aughenbaugh, 2016). The expected outcome on the strength and durability cannot be predicted with confidence based on the observed glass phase and lime values.

Table 6: Summary of weathered fly ash and coal gasification ash differences

| | **Weathered fly ash** | **Coal gasification ash** |
|---|---|---|
| Colour | Dark grey | Light grey |
| Composition | 83% power station fly ash, 17% both gasification ash and bottom ash fines (<250µm) | Coarse gasification ash (>250µm) |
| Particle shape | Mainly spherical | Mainly irregular |
| Glass phase | 10% | 30% |
| Lime content range | 1.91 - 16.62 | 2 -5.5 |

## 2.4 Effects of FA on the properties of concrete

### 2.4.1 FA used as a partial replacement of PC in concrete

Typically, the South African cement manufacturers market Portland fly ash cement; CEMII/A-V 32.5N containing 6-20% fly ash by mass of cement and CEMII/B-V 32.5N containing 21-35% fly ash by mass of cement, both complying with SANS EN 197-1 & 2 code (Kruger, 2003). Cement with 15-20% FA by mass exhibits positive effects on the workability and cost (Zode, 1999), whilst 25-35% FA by mass improves the durability to sulphate attack, alkali-silica expansion and thermal cracking (Mehta, 2004). Cement replacement of FA is useful in lower grades of concrete 20 MPa and 35 MPa, FA at 35% results in considerable increase in strength properties (Nagabhushana, 2015).

### 2.4.2 Effects of FA on workability

Workability is that property of freshly mixed concrete, which determines the ease and homogeneity with which it can be mixed, placed, compacted and finished (American Concrete Institute, Committee 116, 1978). A dry, stiff concrete mix gives a low slump measurement, making it difficult to work (place and compact) with and prone to have larger particles separating from the mix. The ideal concrete mix slump is the driest practicable for placement using the available consolidation equipment (Kosmatka, et al., 2002). The excessive increase of water leads to increased workability but in addition a loss of strength, increased segregation, and honeycombing (Owens, 2009).

Fly ash has been found to improve workability and lower the water demand of concrete (Zode, 1999; Grieve, 2009; Kruger, 1987). A concrete mix with fly ash requires about 1 to 10% less water for a given slump than a concrete mix containing only PC (Kruger, 2003). The fineness of the FA particles occupying the voids for water reduces the water demand, and their spherical shape improves workability (Zode, 1999). A replacement of 10 – 15%, resulted in 10 l/m$^3$ water reduction in concrete, and replacement of 15 – 20% m/m, resulted in 15 – 20 l/m$^3$ water reduction in concrete, in the case of concrete with the equivalent 28-day compressive strengths and a slump of 50 mm (Kruger, 2003).

### 2.4.3 Effects of FA on heat of hydration

The chemical reaction between cementitious material and water is called hydration (Kosmatka, et al., 2002). The hydration process is an exothermic reaction that produces heat when reactants are converted to products contributing to the development of strength and durability in concrete. Peak temperatures are witnessed during the production of CSH and $Ca(OH)_2$ (Marais, 2009 ). FA is commonly used to limit the heat that would have been emitted by only using PC. The NBRI determined the heat of solution of PC/FA blends made with two specially selected fly ashes from Kriel Power Station and Taaibos Power Station, in 1980 (Kruger, 1987). The heat of hydration as a function of FA content is represented in Figure 8, indicating a significant reduction of total heat of hydration with the increase of FA content (Kruger, 2003). A reduction in heat of hydration reduces the potential of thermal cracking (Grieve, 2009). Consequently, there is increased durability of concrete, arising from lower permeability, due to a reduced cracking.

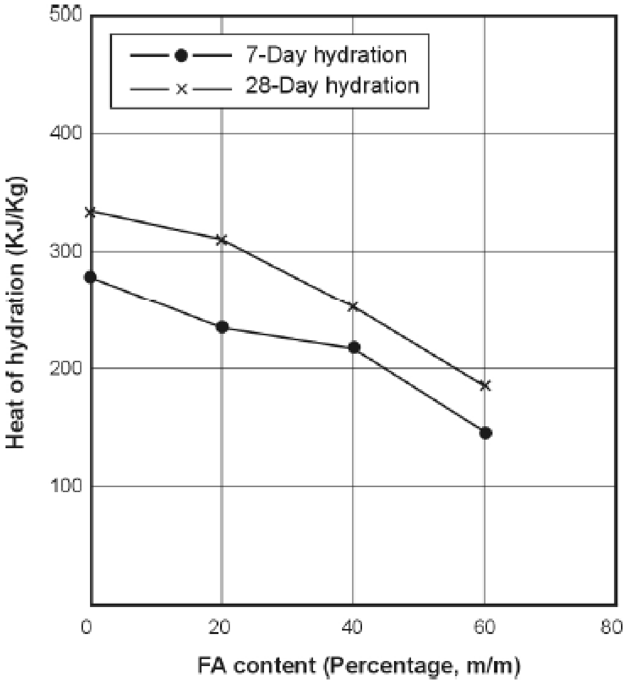

Figure 8: Heat of hydration of PC, and blends of PC and a typical South African FA (Kruger, 2003)

### 2.4.4 Effects of FA on strength development

The addition of FA improves the strength of concrete but retards the rate of strength gain in comparison to PC concrete (Owens, 2009), see Figure 9. The FA blended concrete undergoes two processes to produce calcium silicate hydrate (C-S-H). Therefore, the strength at 28-days is lower, but increases with time (Nagabhushana, 2015). With 20% FA cement replacement improved strength is observed at 56-days, an increase in FA percentage decreases the rate of strength gain (Harison, et al., 2014; Rahul Upadhyay, 2014; Nagabhushana, 2015).

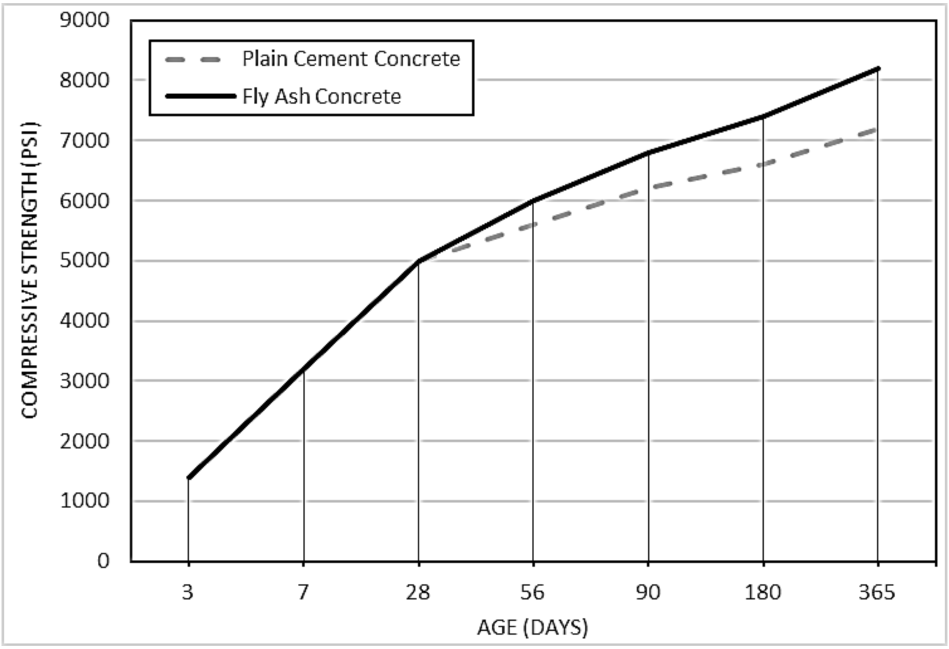

Figure 9: Strength development of Portland cement (faded line) vs fly ash (dark line) with age (Wilmshurst, 2017)

### 2.4.5 Effects of FA on durability

Durability as defined by Ballim *et al.,* (2004) *is the ability of a material or structure to withstand the service conditions for which it is designed over a prolonged period without significant deterioration (as cited* in Kanjee, 2015). It is associated with the deterioration of a material over the intended service life of the structure in a given environment (Ballim, et al., 2009). Durability is related to penetrability of concrete. Concrete is a porous material and the addition of FA creates a discontinuous pore structure and clogs the pore channels with additional C-S-H gel from the consumption of $Ca(OH)_2$ due to the pozzolanic reaction (Shashiprakash, et al., 1994). Increasing FA, decreases penetrability of concrete. The fine particles of fly ash creating a barrier that is hard to penetrate is known as the “packing effect” (Mehta, 2004). The “packing effect” or water tightness enhances durability resisting corrosion, alkali aggregate expansion, excessive bleeding, sulphate attack, freeze-thaw, and alkali-silica expansion (Zode, 1999; Grieve, 2009; Sideris & Konsta-Gdoutos, 1996). The incorporation of fly ash reduced the sorptivity of concrete in early age and yielded better resistance to chloride ion penetration (Nath & Sarker, 2011).The addition of FA improves the durability of concrete by decreasing the chloride conductivity and water sorptivity, whilst increasing the oxygen permeability index (Ballim, et al., 2009) .

Three Durability Index tests namely, the 1) oxygen permeability index (OPI) test, 2) water sorptivity index (WSI) test and 3) chloride conductivity index (CCI) test, were developed in order to measure the durability of concrete (Alexander, et al., 2008). These tests provide an understanding of the transport properties of the concrete specimen (Alexander, et al., 1999) as they indicate the potential ease at which gases, liquids and chemicals understood to contribute to the deterioration of concrete can penetrate. Penetration is mostly governed by the porosity of concrete, presence of cracks, type of cement and the exposure conditions. The OPI test results indicate the permeability of the concrete to gas, the WSI test is an assessment of the microstructural porosity of the near surface concrete and distinguishes from bulk absorption effects and the CCI test is a rapid assessment of the resistance of concrete to ingress of chlorides (Kanjee, 2015; Alexander, et al., 2008; Alexander, et al., 1999). Controlled laboratory studies and site data have been collected with time and analysed to provide durability specifications found in Table 7.

Table 7: Suggested ranges for durability classification using index values (Alexander, et al., 1999)

| Durability class | OPI (log scale) | Sorptivity (mm/√h) | Conductivity (mS/cm) |
|---|---|---|---|
| Excellent | > 10 | < 6 | < 0.75 |
| Good | 9.5 - 10 | 6 - 10 | 0.75 – 1.50 |
| Poor | 9.0 – 9.5 | 10 - 15 | 1.50 – 2.50 |
| Very poor | < 9.0 | > 15 | > 2.50 |

### 2.4.6 Effects of FA on drying shrinkage

Drying shrinkage is the loss of moisture from concrete after it hardens. When concrete is initially exposed to a drying condition - one in which there is a difference between the relative humidity of the environment and that of the concrete - it first loses free water (Owens, 2009). In the larger capillary pores this results in little or no shrinkage. In the finer water-filled capillary pores (2.5 to 50 nm size) due to loss of moisture, curved menisci are formed, and the surface tension of water pulls the walls of the pores. Thus, internal negative pressure develops when the meniscus forms in the capillary pores. This pressure results in a compressive force that leads to shrinkage of concrete. Continued drying also leads to the loss of adsorbed water, a change in the volume of unrestrained cement paste and an increase in the attraction forces between the C-S-H hydration products that leads to shrinkage (Mindess, et al., 2003). The thickness of the adsorbed water layer has been reported to increase with increasing humidity. Therefore, it is conceivable that a higher water content would lead to a thicker layer of adsorbed water, and hence, more drying shrinkage (Concrete Technology in Focus , n.d.). The water/binder ratio, type of supplementary cementitious material, restraints and environment influences the degree of drying shrinkage. To manage drying shrinkage the total water content must be kept as low as practicable for the intended application, see Figure 10. Low water content can be achieved by using a high content of hard, rigid aggregates that are free of clay coatings, and by using mid-range or high-range water-reducing admixtures.

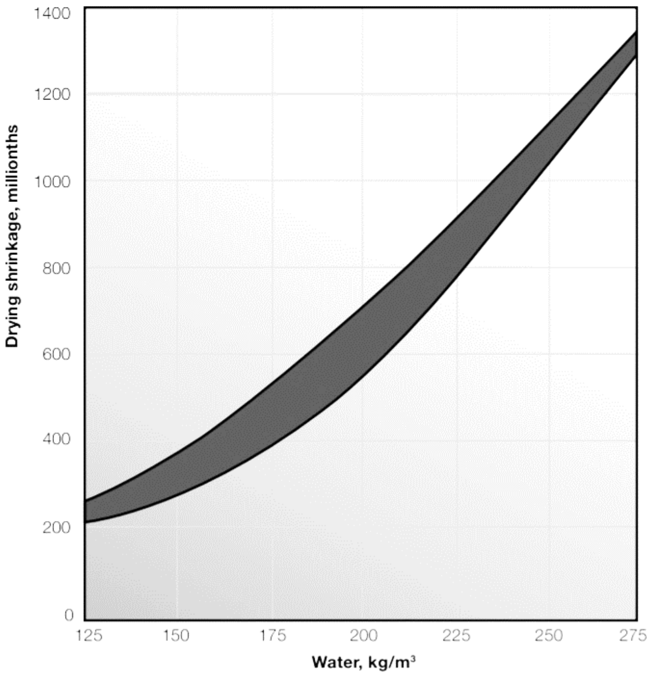

Figure 10: Effect of total water content on drying shrinkage (Shaded area represents data from a large number of mixtures of various proportions.) (Concrete Technology in Focus , n.d.)

The major concern about shrinkage in concrete is the potential for cracking. Cracks are not aesthetically pleasing and if not well managed can rapidly deteriorate a structure. Fly ash in concrete has been found to reduce drying shrinkage (Atis, 2003; Chindaprasirt, et al., 2004). Increased FA replacement levels together with a lower w/b ratio have been reported to increase concrete durability. This is achieved by reducing the cracks that develop due to drying shrinkage (Zode, 1999; Mehta, 2004). Figure 11: Variation of drying shrinkage of concrete with fly ash content demonstrates the positive effects of fly ash on reducing drying shrinkage.

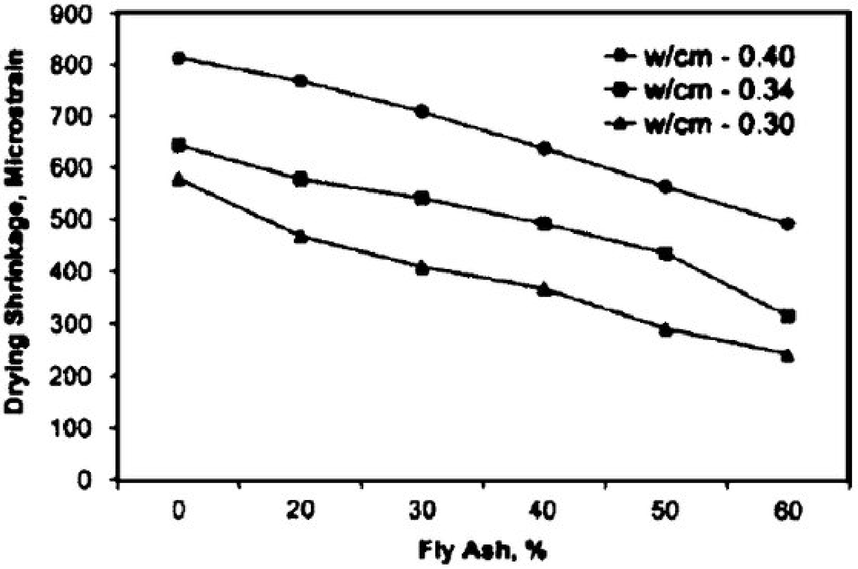

Figure 11: Variation of drying shrinkage of concrete with fly ash content (Kumar, et al., 2007)

## 2.5 Summary of literature review

The literature review has presented the knowledge gained to enable the investigation into the use of weathered fly ash and coal gasification ash as partial replacements for Portland cement in concrete. There was an existing rich history of the use of PC in concrete. The strength and durability properties of PC concrete have been investigated, and the shortfalls have been identified. Extensive research into the use of fly ash as a supplementary cementitious material has been conducted to counter the shortfalls of PC concrete. FA is one of the known and used supplementary cementitious materials to produce blended cements, the other popular two are condensed silica fume (CSF) and ground granulated blast-furnace slag (GGBS). Sasol ashes have been cited as potential supplementary cementitious materials due to the chemical composition similarities they share with FA. The effects of FA on the properties of concrete were studied to enable comparison with the Sasol ashes. It has been found that FA has a positive impact on the fresh and hardened properties of concrete. To follow is the methodology that will enable the comparison between Sasol ashes and FA.

# CHAPTER 3 – METHODOLOGY

## 3.1 Introduction

This chapter presents the experimental variables, materials characterisation, concrete mix designs, casting, specimen preparation and testing details of this investigation.

## 3.2 Experimental variables

The variables considered to have a significant influence on the behaviour of PC concrete were cement type, replacement percentage of PC and water/binder ratio.

### 3.2.1 Cement types

In this investigation, four types of cement blends were used to identify the potential use of CGA and WFA as partial replacements of PC in concrete, 100% PC, PC/WFA, PC/CGA and PC/FA blends. Portland Cement was the recurrent cementitious material in all four blends but at varying percentages.

CEM I 52.5R was available for use in this investigation. The cement was sourced from AfriSam Eikenhof, Roodepoort. The South African FA used was from the Kriel Power Station which receives all its burning coal only from Kriel colliery to ensure a high degree of consistency (Ulula Ash, 2009). It is commercially referred to as Fly Ash Class S. The fly ash conforms to the technical specification SANS 50450-1:2011 (Ulula Ash, 2009).

The WFA and CGA used in this investigation was collected from the SASOL plant in Sasolburg, Free State. CGA was dark grey in colour with fine, medium to large sized particles. The medium to large particles were reduced in size using a jaw crusher. Both Sasol ashes were milled to achieve the required fineness, a vibrating mill was used. The aim was to achieve 100% of the ashes passing the 0.074 mm ( sieve no. 200). Fineness of 100% passing through 0.044 mm (No. 325) sieve could not be achieved due to inadequate equipment.

### 3.2.2 Replacement percentage of PC

Three percentages were chosen to replace PC in concrete, 10%, 15% and 30%. Blended as 90/10, 85/15 and 70/30 for each PC/WFA, PC/CGA and PC/FA respectively. The percentages were chosen cognisant that the South African cement manufacturers market Portland fly ash cement containing 6 to 35% of fly ash by mass of PC (Kruger, 2003). The percentage replacement greater than 50% is considered as high-volume fly ash and requires better handling and curing (Mehta, 2004).

### 3.2.3 Water-to-binder ratio

The water-to-binder (w/b) ratios for the investigation were 0.50 and 0.60. These ratios are commonly used for conventional concrete mixes in the construction and building industry (Grieve, 2009). A lower w/b ratio is expected to result in higher strength, lower permeability, and a reduction in shrinkage strain, whilst the opposite is expected for the higher w/b ratio (Kosmatka, et al., 2002).

## 3.3 Materials characterization

To carry out the experiments PC, South African FA, WFA and CGA were used as the cementitious materials used in both concrete and mortar samples. Coarse and fine aggregate from the andesite rock were used prepare hardened concrete, and only the fine aggregate was used to prepare hardened mortar. The characteristics of the cementitious material and coarse aggregate were investigated using X-ray fluorescence test and sieve analysis, respectively.

### 3.3.1 Cementitious material

The X-ray fluorescence (XRF) test was conducted to determine the chemical composition of WFA, CGA and FA. A loss on ignition (LOI) test was carried out on each SCM. The LOI test is an accepted method for estimating the unburned carbon content (Mohebbi, et al., 2015). The chemical composition of PC was provided by AfriSam and is assumed to have been determined using XRF.

#### 3.3.1.1 Sample preparation

Prior to the XRF test, an LOI test was done. Three grams of SCM samples, WFA, CGA and FA, were placed in to individual crucibles (ceramic or metal container) for testing. The mass of each crucible was measured before and after the sample placement. The crucibles with the sample were placed in a 1050 °C heated furnace for 30 minutes. The crucibles were then removed and allowed to cool to room temperature. The crucibles were weighed to determine the loss in mass. The weighted difference in mass indicated the loss on ignition.

Fused beads were used to determine the chemical composition of WFA, CGA and FA. Each SCM was pulverised and mixed with 2 grams of lithium borate flux to accelerate the fusion process. The mixture was placed in a 5 mm thick by 30 mm diameter disc mould. The discs were exposed to a temperature of 1000 °C for 12 minutes. The samples in the moulds dissolved to become homogenous glass beads. The fused disc preparation eliminates the potentially adverse effects of discrete mineral phases by dissolving the cement in a flux and fusing the mixture into a homogeneous glass disk (Stutzman & Heckert, 2013).

#### 3.3.1.2 Chemical Composition

The LOI and XRF tests on South African FA, CGA and WFA were carried out at the AfriSam Roodepoort laboratory. Table 8 presents the chemical composition of the chemical composition of CEM 52.5R (AfriSam, 2017), South African FA, WFA and CGA. The chemical compounds CaO, $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ are highlighted below. A brief comparison of the XRF results to those from the literature review indicate that only $Al_2O_3$ and CaO of WFA were within the observed ranges. This indicates that not enough Sasol ashes have been analysed to firmly determine their chemical /mineral composition.

Table 8: Chemical composition of fly ash by XRF Chemical composition analysis of CEM I 52.5R, FA, WFA and CGA.

| **Chemical compound (% by mass ignited basis)** | **AfriSam CEM I 52.5R** | **Fly Ash (FA)** | **Weathered Fly Ash (WFA)** | **Coal Gasification Ash (CGA)** |
|---|---|---|---|---|
| Loss of ignition | 2.9 | 1.76 | 11.76 | 6.95 |
| $SiO_2$ | 20.7 | 49.77 | 54.32 | 60.26 |
| $P_2O_5$ | 0 | 1.09 | 0.95 | 0.66 |
| $Al_2O_3$ | 4.6 | 31.88 | 26.69 | 21.52 |
| $Fe_2O_3$ | 2.6 | 2.8 | 5.23 | 3.97 |
| CaO | 65 | 7.83 | 9.8 | 7.6 |
| MgO | 1.7 | 2.01 | 2.78 | 1.7 |
| $K_2O$ | 0.4 | 1.07 | 1.02 | 1.13 |
| $TiO_2$ | 0.3 | 1.78 | 1.56 | 1.28 |
| $Na_2O$ | 0.1 | 0.3 | 1.33 | 0.37 |
| $Mn_2O_3$ | 0.1 | 0.04 | 0.08 | 0.03 |
| $SO_3$ | 2.9 | 0.02 | 0.03 | 0.01 |
| Total | 101.3 | 100.35 | 115.55 | 105.48 |
| CaO | 64% | 8% | 8% | 7% |
| $SiO_2$, $Al_20_3$, $Fe_2O_3$ | 28% | 84% | 75% | 81% |

### 3.3.2 Aggregate

Andesite is the second most easily available igneous rock, following quartzite and sandstone (Grieve, 2009). 13.2 mm andesite stone was used as coarse aggregate and unwashed crusher sand was used as fine aggregate. The grading curve of the crusher sand is depicted in Figure 12.

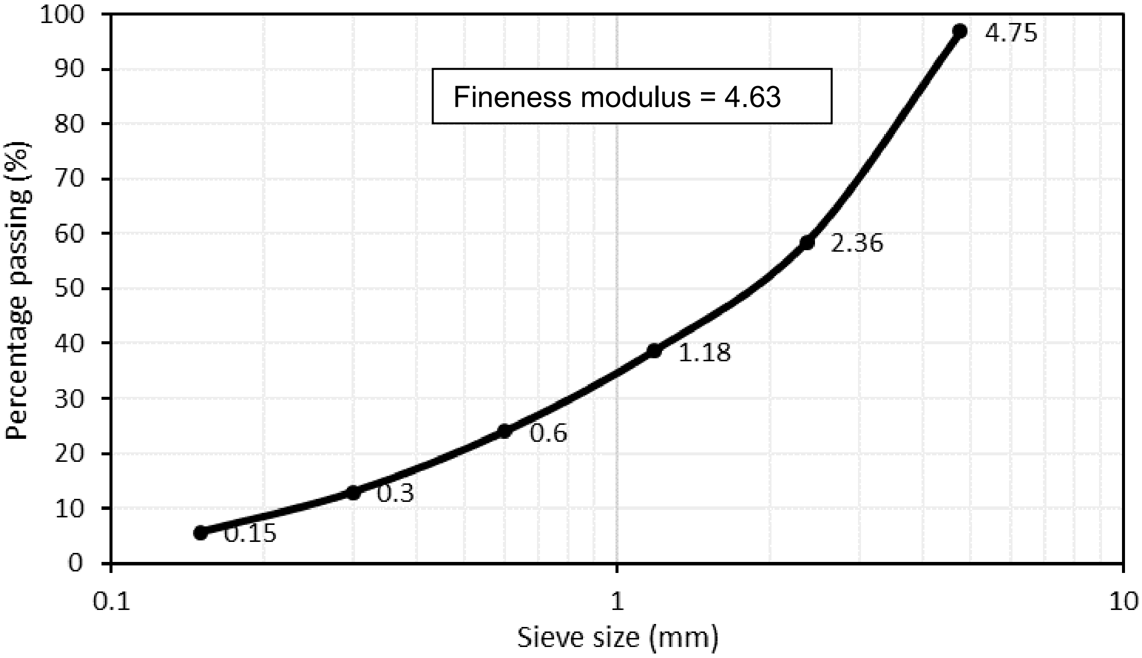

Figure 12: Grading curve of andesite crusher sand

## 3.4 Concrete mix design

The concrete mix design used in this investigation was determined using the 9th edition of Fulton's Concrete Technology. The coarse aggregate was omitted in the mortar mix design, but the same design principles were used.

### 3.4.1 Concrete mix design and proportions

The concrete mix designs used in this investigation for 0.50 and 0.60 water-to-binder ratios are presented in Table 9 and Table 10 respectively.

Table 9: Concrete mix design for 0.50 water-to-binder ratio

| **Ingredient** | **0.5 water-to-binder ratio** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0%** | **10%** | | | **15%** | | | **30%** | | |
| | | **FA** | **WFA** | **CGA** | **FA** | **WFA** | **CGA** | **FA** | **WFA** | **CGA** |
| PC (kg/m$^3$) | 440 | 396 | 396 | 396 | 374 | 374 | 374 | 308 | 308 | 308 |
| FA (kg/m$^3$) | - | 44 | - | - | 66 | - | - | 132 | - | - |
| GCA (kg/m$^3$) | - | - | 44 | - | - | 66 | - | - | 132 | - |
| WFA (kg/m$^3$) | - | - | - | 44 | - | - | 66 | - | - | 132 |
| SAND (kg/m$^3$) | 917 | 904 | 904 | 904 | 897 | 897 | 897 | 877 | 877 | 877 |
| STONE (kg/m$^3$) | 793 | 793 | 793 | 793 | 793 | 793 | 793 | 793 | 793 | 793 |
| WATER (l/m$^3$) | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 |

Table 10: Concrete mix design for 0.60 water-to-binder ratio

| **Ingredient** | **0.6 water-to-binder ratio** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0%** | **10%** | | | **15%** | | | **30%** | | |
| | | **FA** | **WFA** | **CGA** | **FA** | **WFA** | **CGA** | **FA** | **WFA** | **CGA** |
| PC (kg/m³) | 370 | 333 | 333 | 333 | 314 | 314 | 314 | 259 | 259 | 259 |
| FA (kg/m³) | - | 37 | - | - | 55 | - | - | 111 | - | - |
| GCA (kg/m³) | - | - | 37 | - | - | 55 | - | - | 111 | - |
| WFA (kg/m³) | - | - | - | 37 | - | - | 55 | - | - | 111 |
| SAND (kg/m³) | 977 | 904 | 904 | 904 | 960 | 960 | 960 | 943 | 943 | 943 |
| STONE (kg/m³) | 793 | 793 | 793 | 793 | 793 | 793 | 793 | 793 | 793 | 793 |
| WATER (l/m³) | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 |

## 3.4.2 Mortar mix design and proportions

The mortar mix proportions used in this investigation to measure the drying shrinkage of hardened mortar are presented in Table 11 and Table 12.

Table 11: Mortar mix design for 0.50 water-to-binder ratio

| | **0.5 water-to-binder ratio** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0%** | **10%** | | | **15%** | | | **30%** | | |
| | | **FA** | **WFA** | **CGA** | **FA** | **WFA** | **CGA** | **FA** | **WFA** | **CGA** |
| PC (kg/m³) | 440 | 396 | 396 | 396 | 374 | 374 | 374 | 308 | 308 | 308 |
| FA (kg/m³) | - | 44 | - | - | 66 | - | - | 132 | - | - |
| GCA (kg/m³) | - | - | 44 | - | - | 66 | - | - | 132 | - |
| WFA (kg/m³) | - | - | - | 44 | - | - | 66 | - | - | 132 |
| SAND (kg/m³) | 917 | 904 | 904 | 904 | 897 | 897 | 897 | 877 | 877 | 877 |
| WATER (l/m³) | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 |

Table 12: Mortar mix design for 0.60 water-to-binder ratio

| | **0.6 water-to-binder ratio** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0%** | **10%** | | | **15%** | | | **30%** | | |
| | | **FA** | **WFA** | **CGA** | **FA** | **WFA** | **CGA** | **FA** | **WFA** | **CGA** |
| PC (kg/m³) | 370 | 333 | 333 | 333 | 314 | 314 | 314 | 259 | 259 | 259 |
| FA (kg/m³) | - | 37 | - | - | 55 | - | - | 111 | - | - |
| GCA (kg/m³) | - | - | 37 | - | - | 55 | - | - | 111 | - |
| WFA (kg/m³) | - | - | - | 37 | - | - | 55 | - | - | 111 |
| SAND (kg/m³) | 977 | 904 | 904 | 904 | 960 | 960 | 960 | 943 | 943 | 943 |
| WATER (l/m³) | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 | 220 |

## 3.5 Casting, specimen preparation and testing

All concrete and mortar mixes were exposed to ambient temperatures and a dry indoor environment during handling and preparation. The work area was protected from direct sunlight. The total number of specimens prepared was influenced by the specific test standard or manual, number of cement types, number of water-to-binder ratios and the number of PC percentage replacements.  More than one specimen was prepared per test to account for variability. Casting was done according to SANS5861-2 (1994).

### 3.5.1 Slump test of freshly mixed concrete

The slump test is used as an indicator of the concrete mix (Grieve, 2009). Workability is dependent on the physical and chemical properties of the individual components making up the concrete mix and the proportions of each in the concrete (Daniel, 1994). The slump measurements of WFA and CGA were compared to those from FA and 100% PC concrete batches. The slump tests were carried out according to SANS 5862-1:2006. Slump measurements in the range of 25 to 100 mm requiring moderate vibration and 75 to 150 mm requiring hand compaction (Addis & Goodman, 2009), were considered favourable.

#### 3.5.1.1 Slump test procedure

A sample concrete mix from a static pan-type mixer was placed into a dampened galvanised sheet metal cone in three approximately equal parts with each layer subjected to 25 evenly distributed blows from the tamping rod. The cone was firmly held in place by standing on the side foot pieces. Once the final layer was tamped, the surface of the cone was levelled off by rolling the tamping rod over the mouth of the cone. The cone was carefully removed from the moulded concrete, inverted to be placed with the mouth on the floor and the tamping rod placed atop to be used as the datum of the slump. Slump measurements were taken from the soffit of the tamping rod to the highest point of the concrete. The slump shape was observed to discern whether the mix provided a true (ideal), shear (lack of cohesiveness) or collapse (high water content) slump. After testing the sampled concrete was thoroughly mixed back into the batch.

### 3.5.2 Compressive and Tensile splitting strength tests

The compressive strength test was chosen to determine the effect of cement type, percentage replacement of PC and water-to-binder ratio on concrete strength. The compressive strength of concrete is of primary importance in structural applications because it gives a direct indication of its capacity to resist loads, and it is required in the design procedures (Carino, 1994).

The tensile splitting test was conducted to give an indication of cracking resistance. There are currently no standardized test procedures for determining the direct tensile splitting strength of concrete, that is, the strength under uniaxial tension (Carino, 1994).

### 3.5.2.1 Type of specimens

The compressive and tensile strength test was determined using 100 mm concrete cubes. The four types of cementitious material, PC, South African FA, WFA and CGA were used in 100%, 10%, 15% and 30% proportions, for each of the two water-to-binder ratios, 0.50 and 0.60. The compressive strength test required more cubes as it was carried out on testing ages 7, 28 and 56-day, and tensile splitting strength test was carried out on 28-days only.

### 3.5.2.2 Number of specimens

The total number of 100 mm concrete cubes prepared for the compressive and tensile splitting strength tests considering both water-to-binder ratios, was 240. The number of specimens prepared for each concrete mix is shown in Table 13.

Table 13: Number of concrete specimens prepared for strength testing per w/b ratio

| | Total number of specimens for each water-to-binder ratio | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100% PC | PC/FA | | | PC/WFA | | | PC/CGA | | | |
| **Concrete Mix** | | **90/10** | **85/15** | **70/30** | **90/10** | **85/15** | **70/30** | **90/10** | **85/15** | **70/30** | **TOTAL** |
| Compressive | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 90 |
| Tensile Splitting | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 30 |

### 3.5.2.3 Casting and curing of specimens

SANS 5861-3:2006 was used for the making and curing of the 100 mm cube specimens using plastic moulds. Concrete-filled plastic cubes were compacted by vibration using a vibrating table for 2 minutes. The specimens were covered with an impervious sheet and then stored for 24 hours. Marking of the specimens was done after 24 hours. The specimens were demoulded and left to cure in a water bath at 22±3°C until the specified testing age.

### 3.5.2.4 Compressive and tensile strength testing

The compressive strength test was carried out in accordance to SANS 5863:2006. The saturated-surface-dry mass of each concrete cube was measured prior to crushing. The test was conducted in a hydraulic concrete cube press machine. The concrete cube was placed at the centre of the platform and loaded continuously without shock at a uniform rate of 0.3 MPa/s ± 0.1 MPa/s (SANS5863:2006) until failure.

The tensile splitting strength test was carried out in accordance with SANS 6253:2006. The saturated mass of each concrete cube was measured prior to testing. The test was conducted in a hydraulic concrete cube press machine. The concrete cube was placed between half-moon attachments, aligning the crest and trough to the centre of the cube. The cube was loaded at a rate of 15kN/min until failure.

### 3.5.3 Drying Shrinkage test

The drying shrinkage was measured to determine the shrinkage strain of WFA and CGA with the specified w/b ratios and percentages of replacement. Shrinkage is a common phenomenon encountered in almost every cementitious product due to contraction of total mass upon loss of moisture (Rao, 2001).

#### 3.5.3.1 Type of specimens

The drying shrinkage strain was determined from 50 x 50 x 300 mm mortar rectangular prisms. The three supplementary cementitious materials, South African FA, WFA and CGA were used in 10%, 15% and 30% proportion. For each of the two water-to-binder ratios, 0.50 and 0.60.

#### 3.5.3.2 Number of specimens

A total of sixty 50 x 50 x 300 mm mortar prisms for both water-to-binder ratios were cast and measured for drying shrinkage. Three prisms were prepared for each mortar mix, as shown in Table 14:

Table 14: Number of concrete specimens prepared for drying shrinkage testing per w/b ratio

| | Total number of specimens for one water-to-binder ratio | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100PC | PC/FA | | | PC/WFA | | | PC/CGA | | | |
| **Concrete Mix** | | **90/10** | **85/15** | **70/30** | **90/10** | **85/15** | **70/30** | **90/10** | **85/15** | **70/30** | **TOTAL** |
| Drying shrinkage | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 30 |

#### 3.5.3.3 Casting and curing of specimens

The 50 x 50 x 300 mm rectangular mortar prisms were cast in steel moulds accommodating 6 at a time. The steel moulds had six Ø10 mm holes along the cross section of each specimen allowing for the insertion of the 20 mm long M6 bolts. The 20 mm M6 bolts were held in place by M6 nuts, preventing movement during the compaction by vibration of mortar in the mould. The prisms were covered with an impervious sheet for 24 hours, and then placed in a water bath at 22±3°C to cure for 2 days. Three days of curing was selected to improve bond strength and prevent the rapid moisture loss that would result in excessive shrinkage (Alexander, 2009). Figure 13 illustrated the hardened rectangular prism which was stored and measured in a temperature monitored room.

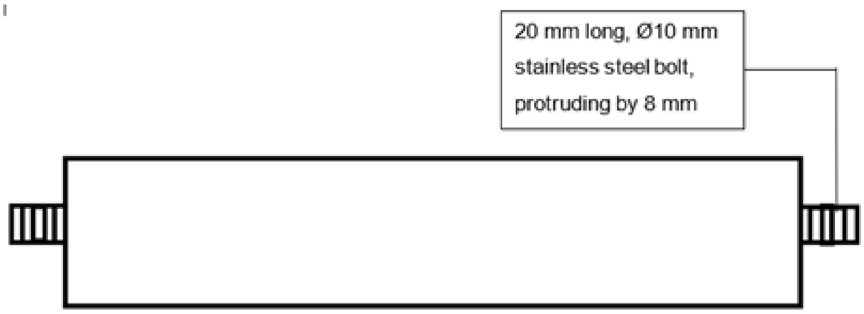

Figure 13: Hardened 50 x 50 x 300mm rectangular mortar prism measured during the drying shrinkage test

### 3.5.3.4 Drying shrinkage test

A digital gauge was used to measure drying shrinkage. The digital gauge was fastened onto a length comparator to measure the change of length 50 x 50 x 300 mm prism. A 330 mm long steel rod was used to zero the dial gauge, establishing a reference point for the 50 x 50 x 300 mm prisms to be measured from, as shown in Figure 14. The prisms were stored and measured in a room with temperatures and humidity range, 12-16 °C and 45-65 % respectively.

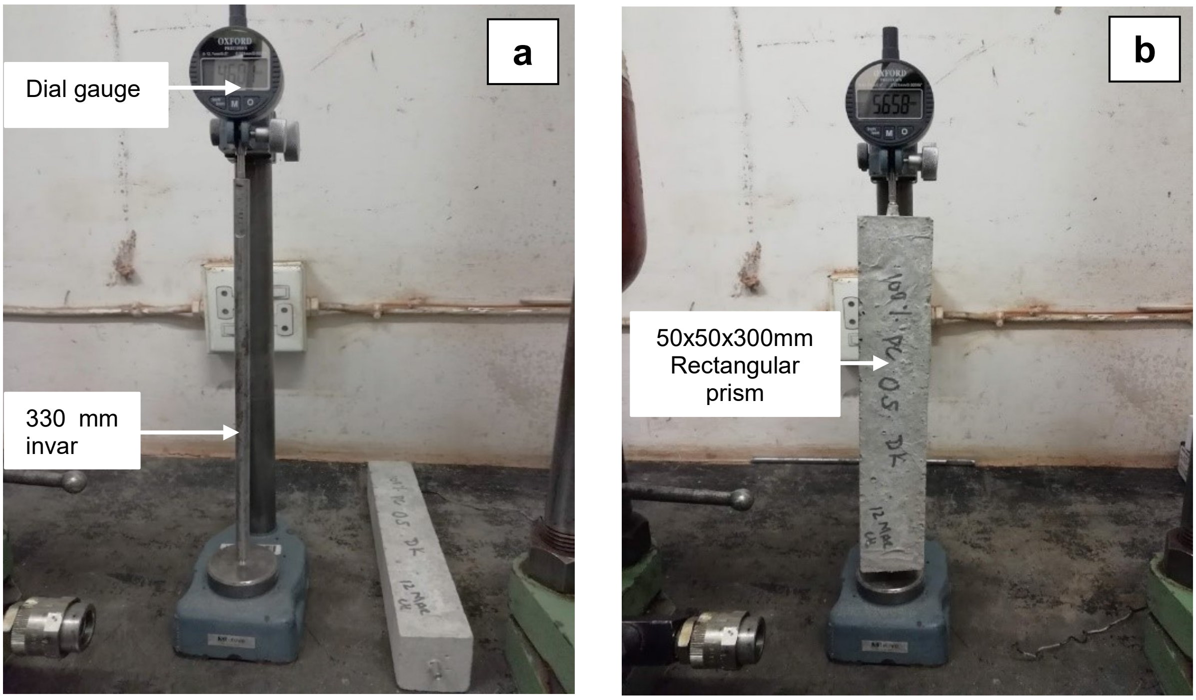

Figure 14: Photograph of length comparator a) to zero dial gauge b) measuring drying shrinkage

The drying shrinkage strain (ε) was determined using the following equation:

$$\varepsilon = \frac{L_n - L_{n-1}}{L_0} \qquad \text{Equation 1}$$

where

$\varepsilon$ = drying shrinkage strain
$n$ = number of measurements
$L_n$ = current measurement (μm)
$L_{n-1}$ = previous measurement (μm)
$L_0$ = initial length of specimen, 300 mm

### 3.5.4 Durability Index tests

The durability index (DI) tests were performed to measure the resistance of cement blends, PC/WFA, PC/CGA and PC/FA, at two different w/b ratios and three replacement percentages to permeation, absorption and diffusion. Durability index tests provide an indication of the concrete's durability in an aggressive environment, such as one with high a sulphate concentration. Three durability index tests were performed:

- Chloride conductivity index test – SANS 3001-CO3-3:2015
- Water sorptivity index test –DI Manual 2018
- Oxygen permeability index test – SANS 3001-CO3-2:2015

The results obtained from the cement blends were compared to those of 100% PC concrete. The durability index tests were carried out according to the methods recommended in the DI Manual 2018.

#### 3.5.4.1 Type of specimens

The durability indexes were determined from Ø 70 ± 2 mm and 30 ± 2 mm thick concrete discs cored and cut from 100 mm cubes as shown in Figure 15. The three supplementary cementitious materials, South African FA, WFA and CGA were used in 10%, 15% and 30% proportion. For each of the two water-to-binder ratios, 0.50 and 0.60.

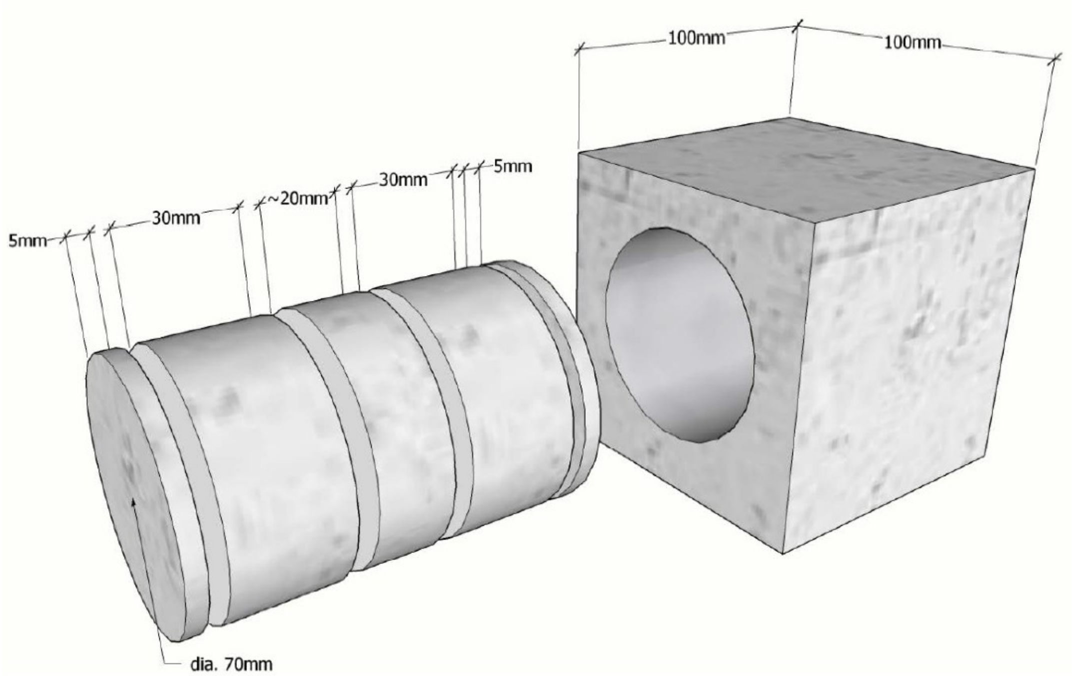

Figure 15: 100mm concrete cube cored and cut for Ø70±2mm and 30±2mm thick concrete discs (DI Manual, 2018)

The durability index tests were carried out according to the Durability Index Manual (DI Manual, 2018), at a testing age of 28-days. After extraction, the discs were placed in a ventilated 50 ± 2 °C oven for 7 to 8 days. Prior to the oxygen permeability and chloride conductivity test the concrete discs were placed in a desiccator for 2 to 4 hours to allow for cooling. The thickness and diameter of each specimen was measured at four random points to an accuracy of 0.02 mm using a Vernier calliper. The tests were conducted within 30 minutes of the concrete discs being removed from the desiccator.

#### 3.5.4.2 Number of specimens

Table 15 shows the number of concrete discs required per concrete mix to perform the durability index tests per water-to-binder ratio. Two cubes provided four concrete discs. The same discs were used in the oxygen permeability and water sorptivity tests, as permitted by the Durability Index Manual (DI Manual, 2018). Each oxygen permeability test was conducted prior to the corresponding water sorptivity test, based on the assumption that the oxygen permeability test has a negligible impact on the microstructure of the concrete specimen. A total of 160 concrete discs were prepared and tested.

Table 15: Number of concrete specimens prepared for durability index testing per w/b ratio

| | Total number of specimens for a water-to-binder ratio | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100PC | PC/FA | | | PC/WFA | | | PC/CGA | | | |
| **Concrete Mix** | | **90/10** | **85/15** | **70/30** | **90/10** | **85/15** | **70/30** | **90/10** | **85/15** | **70/30** | **TOTAL** |
| Water sorptivity | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 40 |
| O2 Permeability | | | | | | | | | | | |
| Cl Conductivity | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 40 |

### 3.5.4.3 Durability index tests

**Oxygen permeability test**

Permeability cells were pressurised with oxygen to approximately 100±5 kPa. During the test the only outlet for the pressurized oxygen was through the concrete sample. Each concrete was tested to determine the oxygen permeability index.

Test apparatus

Figure 16 shows the arrangement of the permeability cell. A permeability cell of volume approximately 5 litres, capable of withstanding 120 kPa without expansion or contraction was used. Atop the permeability cell was a rigid sleeve. The rigid sleeve accommodated a compressible rubber collar with Shore hardness 39A and allowed for a tight fit of the concrete discs. A tight fit eliminates any leakage of oxygen, except through the pores of the specimen. The rigid sleeve was sealed with a cover plate held firmly in place by a top screw.

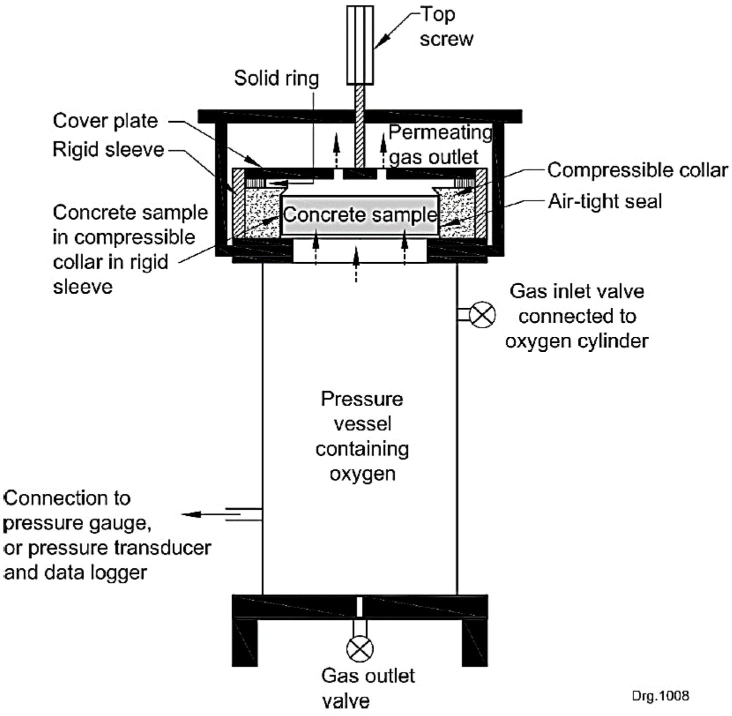

Figure 16: Permeability cell arrangement (DI Manual, 2018)

Test method

To prepare for the initiation of the test, after the concrete discs were fixed in place, oxygen was let into the permeability cell for 5 seconds through the inlet valve and let out through the outlet valve to purge the cell of other gases. Oxygen was then filled to a pressure of about 100±5 kPa, read from the pressure gauge. The pressure gauge was read after 5 minutes to ensure that the pressure had not dropped by 5 kPa or more. If this was so, the procedure was redone to eliminate any leakage. The test was started and recorded electronically on a computer. The test was terminated when the pressure dropped to about 50 kPa or after 6 hours, whichever came first. At the end of the test the top screw was loosened, and the rigid sleeve and concrete specimen removed, to be used in the water sorptivity test.

Calculation of Permeability

The *coefficient of permeability* (*k*) of each specimen in metres per second was determined.

Using the *coefficient of permeability* equation:

$$\mathrm{k} = \frac{\omega \mathrm{Vgd}}{\mathrm{RA}\delta \mathrm{t}} \ln \frac{\mathrm{P_0}}{\mathrm{P}} \qquad \text{Equation 2}$$

where:

$k$ = coefficient of permeability (m/s)
$\omega$ = molecular mass of permeating air (kg/mol)
V = volume of the pressure cylinder ($m^3$)
g = acceleration due to gravity ($m/s^2$)
d = specimen thickness (m)
R = universal gas constant (Nm/Kmol)
A = cross-sectional area of specimen ($m^2$)
$\delta$ = absolute temperature (K)
t = time (s)
$P_0$ = pressure at the start of test (kPa)
P = pressure at time t (kPa)

The oxygen permeability index (OPI) was given as the average of the individual OPI values of the specific concrete blend specimens. OPI was defined as the negative logarithm of the *coefficient of permeability*:

$$\mathrm{OPI} = -\log_{10}\mathrm{k} \qquad \text{Equation 3}$$

### Water sorptivity test

The sorptivity test was done to measure the capacity of the concrete sample to absorb moisture by capillary action. A calcium hydroxide solution was prepared as indicated in the Durability Index Manual (2017) and poured into a shallow tray lined with absorbent towels. Concrete specimens were placed in the solution for the specified times and placed on a weighing scale to measure their mass. The change in mass helped to determine the sorptivity index of the concrete cement blend.

Test apparatus

A plastic 20 mm deep tray was used and layered by absorbent paper towels. A stop watch was used to ensure that the mass of each concrete specimen was measured on a weighing scale at 3, 5, 7, 9, 12, 16, 20 and 25 minutes.

Test method

The perimeter closest to the outer face of each concrete disc was sealed with an impermeable material. The mass of the concrete plus the impermeable material was measured and regarded as the initial mass. The specimens were then placed in the plastic tray with the $Ca(OH)_2$ solution. The depth of the solution was to remain within the thickness of the impermeable material to prevent absorption through the perimeter.

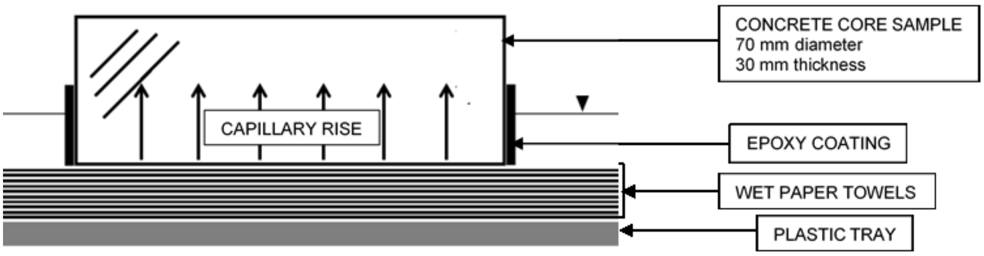

Figure 17: Schematic diagram of water sorptivity test

A stopwatch was used to measure the mass of the specimens at 3, 5, 7, 9, 12, 16, 20 and 25 minutes. After the mass at the 25th minute was recorded, the specimens were placed in a vacuum saturation tank without removing the impermeable material. The tank was evacuated and maintained between -75 kPa and -80 kPa for 3 hours ± 15 minutes. The tank was then isolated and $Ca(OH)_2$ was allowed into the tank until the level was approximately 40 mm above the top specimen(s). The pressure was then re-established to between -75 kPa and -80 kPa and maintained for 1 hour ± 15 minutes. The vacuum was released, and air allowed to enter. The specimens were left to soak for 18 ± 1 hour. This was done to achieve and measure the saturated mass of the specimen.

Calculation of Sorptivity

The water sorptivity (*S*) was calculated as the average of the individual sorptivity values of the specific cement blend using the water sorptivity (*S*) equation:

$$S = \frac{Fd}{M_{SV} - M_{S0}} \qquad \text{Equation 4}$$

where

F = slope of the best fit line (g/√hr)

d = average specimen thickness to the nearest 0.02 mm (mm)

$M_{SV}$ = vacuum saturated mass to the nearest 0.01 g of the specimen (g)

$M_{S0}$ = mass to the nearest 0.01 g of the specimen at the initial time $t_0$ (g)

## Chloride conductivity test

The chloride test involves measuring diffusion which is an internal transport mechanism for a concrete structure exposed to salts (Kanjee, 2015). A 5M sodium chloride solution was prepared according to the Durability Index Manual (2017). The dry masses of the specimens were measured prior to NaCl saturation.

Test apparatus

A conduction cell with anode and cathode parts permanently marked on the outside of the cell was used, illustrated in Figure 18. Power supply was by means of a stabilized DC power supply (0 V to 12 V, 0 A to 1 A) and measurements were recorded using a digital voltmeter and ammeter capable of displaying four-digits, 0 V to 20 V range, 0 mA to 300 mA.

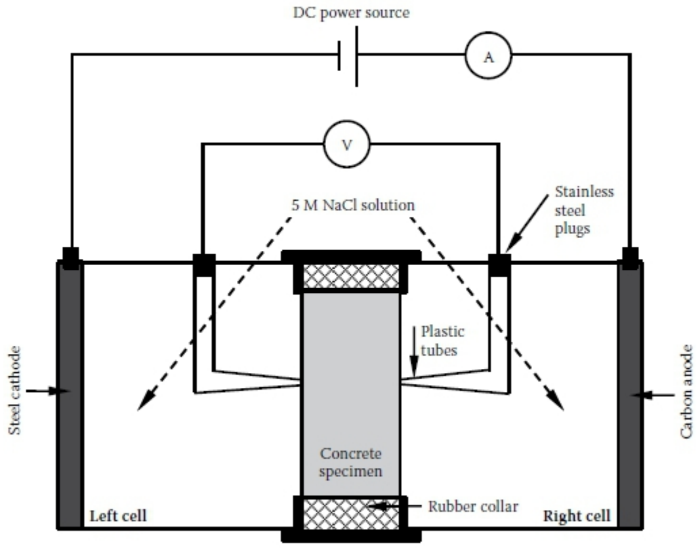

Figure 18: Chloride conductivity set-up (Alexander, et al., 2001)

Test method

The vacuum saturation tank was evacuated and maintained to between -75 kPa and -80 kPa for 3 hours ± 15 minutes. The tank was then isolated and filled with the salt solution until the water level was 40 mm above the top of the specimen(s). The vacuum was re-established and maintained to between -75 kPa and -80 kPa for 1 hour ± 15 minutes. Thereafter, air was allowed into the chamber. The specimens were left to soak in the salt solution for 18±1 hour. The specimens were removed from the solution and placed on the weighing scale to measure their saturated mass. They were then placed in a conduction cell filled with the salt solution and connected accordingly to the anode and cathode wires. The power supply was switched on together with the voltmeter and ammeter to record the current and voltage readings. The movement of chloride ions occurred due to the application of a 10V potential difference. The chloride conductivity was determined by measuring the current flowing through the concrete specimens. Testing was completed within 15 minutes of removing the specimen from the salt solution.

Calculation of Conductivity

The chloride conductivity was calculated as the average of the individual conductivity values of the specific cement blends using the chloride conductivity (δ) equation:

$$\sigma = \frac{\mathrm{id}}{\mathrm{VA}} \qquad \text{Equation 5}$$

where

$\sigma$ = chloride conductivity of the specimen (mS/cm)

i = electrical current (mA)

d = average thickness of specimen (cm)

V = voltage difference (V)

A = cross sectional area of the specimen ($cm^2$)

## 3.6 Investigational flow chart

This flow chart illustrates the process undertaken in this investigation from preparation of fresh concrete, preparation of hardened concrete and mortar concrete, testing to compilation of report. The small circle in the chart indicate the sequence of events. There were two independent events that fed into the main sequence of events which can be identified by capitalised alphabets.

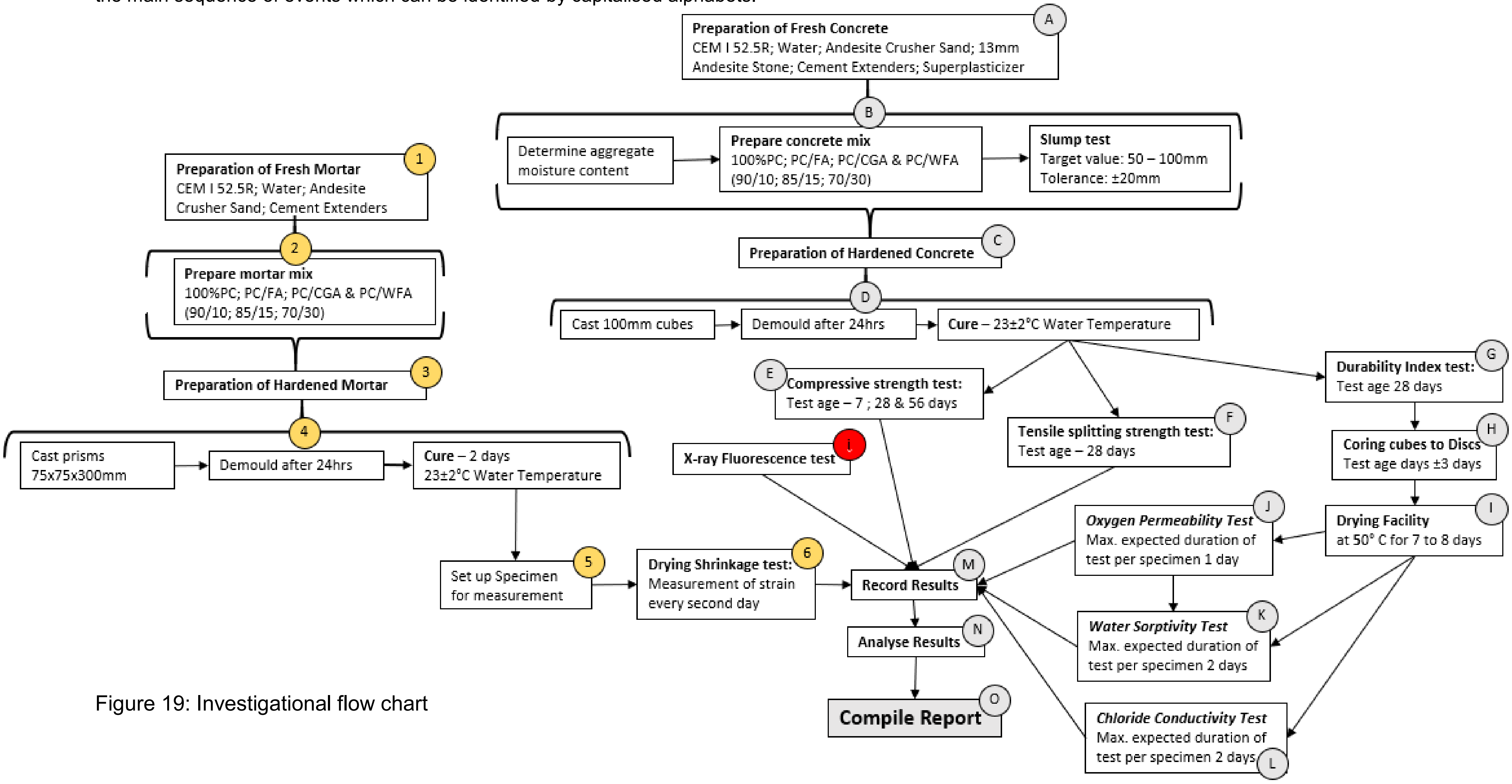

Figure 19: Investigational flow chart

# CHAPTER 4 – RESULTS AND DISCUSSION

## 4.1 Introduction

This chapter presents the tests undertaken and the results of this investigation. Each test is presented in a section with subsections structured as follows;

- Section overview
- Influence of water-to-binder ratio on the test result
- Influence of binder type on the test results, and
- Influence of replacement level on the test result.

To enable comparison of the results, the means of three or four test specimens per cement blend were calculated for each test and analysed. Descriptive and quantitative methods were used to analyse the results. Descriptive analysis is used to discuss observed trends.

Statistical calculations were carried out for the quantitative analysis. The standard deviation of each set of results was determined to measure variation from the mean. A 95% confidence level was selected. The statistic calculations for each test can be found in Appendix A to G. The statistical method ANOVA (analysis of variance) was used to test the variation between the means (Underhill & Bradfield, 2007). This was done by calculating p -values which indicate statistical significance in difference of the data. In this investigation, the p-values were calculated to determine the statistical difference between the SCMs and plain PC blend (100% PC), and between the Sasol ashes (WFA and CGA) and FA blends. A p-value of less than 0.05, will indicate a significant difference between any two blends; meaning there is less likelihood that the two blends will have similar behaviour. A p-value that is greater than 0.05, is interpreted to indicate a correlation between any two blends, meaning there is a high probability that the blends being considered will have similar results or behaviour. The error bars were determined by using the 95% confidence interval with the two-tailed t-distribution (Rumsey, 2012). Grubb's outlier test was used to identify and remove any outliers in the results. Further details on the t-distribution and Grubb's outlier test are captured in Appendix H.

This investigation attempts to answer the question, "Does WFA and CGA have the potential to be used as partial replacements for PC in concrete?" The XRF test carried out on FA, CGA, and WFA indicated a similarity in their chemical compositions. These XRF test results were compared to that of AfriSam CEM I 52.5R chemical composition and the similarities were observed. Furthermore, Mahlaba (2006) and Matjie, et al. (2005) have reported that the physical characteristics of Sasol ashes are comparable to that of FA. Based on the aforementioned results, it has been hypothesized that CGA and WFA blends will have test results and behaviour that is similar to that of 100% PC and FA blends. In this analysis, influence is defined as the ability to have an effect on the concrete properties. 100% PC concrete is used as the primary control for the FA, WFA and CGA blended binder concretes, while the FA blended binder concrete is considered as the secondary control for the WFA and CGA blended binder concretes. The names of the concrete per cement have been abbreviated for ease of writing,

- 15% CGA-0.60 refers to a concrete blend of 85% of PC, 15% of coal gasification ash and with a 0.60 w/b ratio,
- CGA-0.60 refers to CGA concrete blends at all replacement levels (10%, 15% and 30%) for PC and with a 0.60 w/b ratio.
- 15% CGA refers to CGA concrete blends of 15% replacement level for PC of each w/b ratio, 0.50 and 0.60.

## 4.2 Slump measurements

The slump measurements of the concrete mixes; PC, WFA, FA and CGA are presented and discussed in this section. The results in the subsections indicate the influence of w/b ratio, binder type and percentage replacement of plain PC on slump measurements. Additional information on slump measurements can be found in Appendix A. According to literature, favourable slump measurements are within 25-100 mm which requires moderate vibration and 75-150 mm suitable for hand compaction (Addis & Goodman, 2009).

### 4.2.1 Influence of w/b ratio on slump measurements

Higher slump measurements were obtained in the concrete mixes with 0.60 water-to-binder ratio compared to the concrete mixes with 0.50 w/b ratio, similar results have been obtained by other researchers (Addis & Goodman, 2009; Alexander, 1998; Babu & Prasad, 2012).

The FA concrete with the highest PC replacement and highest w/b ratio did not have the highest slump measurement. 15% FA-0.60 had the highest slump measurement of 110 mm (see Figure 20). From the concrete slumps obtained, FA-0.60 concretes will require hand compaction during placement, while all the FA-0.50 concrete will require moderate vibration during placement.

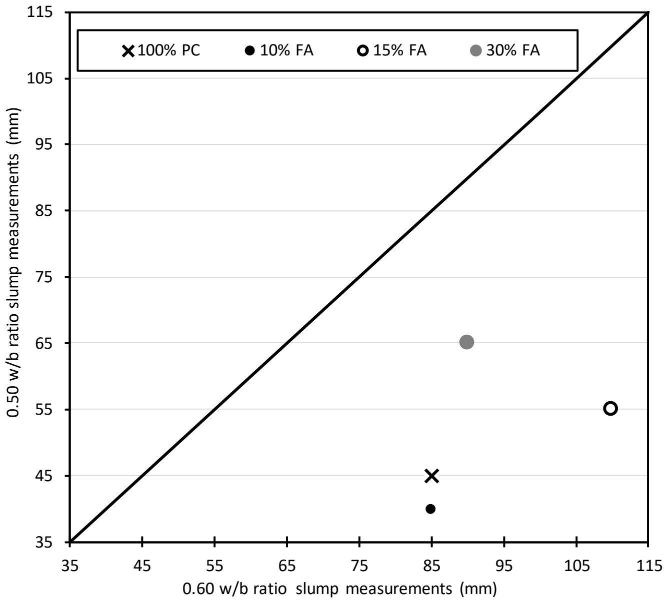

Figure 20: Influence of w/b ratio on the slump measurements of FA

The WFA concrete with the highest replacement level for PC and the highest w/b ratio did not have the highest slump measurement. The 15% WFA-0.60 concrete had the highest slump measurement of 95 mm (see Figure 21). Based on findings by Addis & Goodman, 2009, slump measurements in the range of 25 to 100 mm require moderate vibration whilst those within 75 to 150 mm require hand compaction. The slump measurements observed suggest that WFA-0.60 concrete mixes will require hand compaction during handling, while those of WFA-0.50 will require moderate vibration.

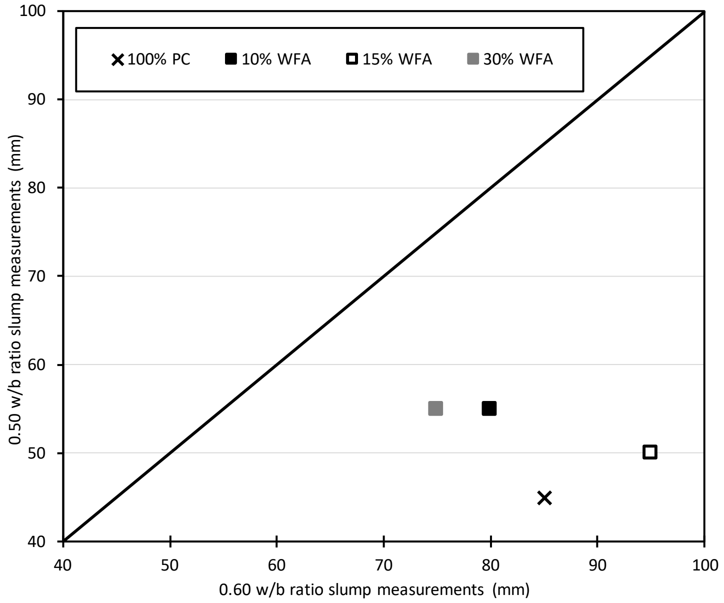

Figure 21: Influence of w/b ratio on the slump measurements of WFA

The CGA concrete with the highest replacement level for PC and the highest w/b ratio had the highest slump measurement. The 30% CGA-0.60 concrete had the highest slump measurement of 140 mm (see Figure 22). The slump measurements of the CGA-0.50 concretes were greater than that of the 100% PC-0.50 (45 mm) concrete. The CGA-0.60 concrete mixes would require hand compaction during handling, while all the CGA-0.50 concrete mixes would require moderate vibration.

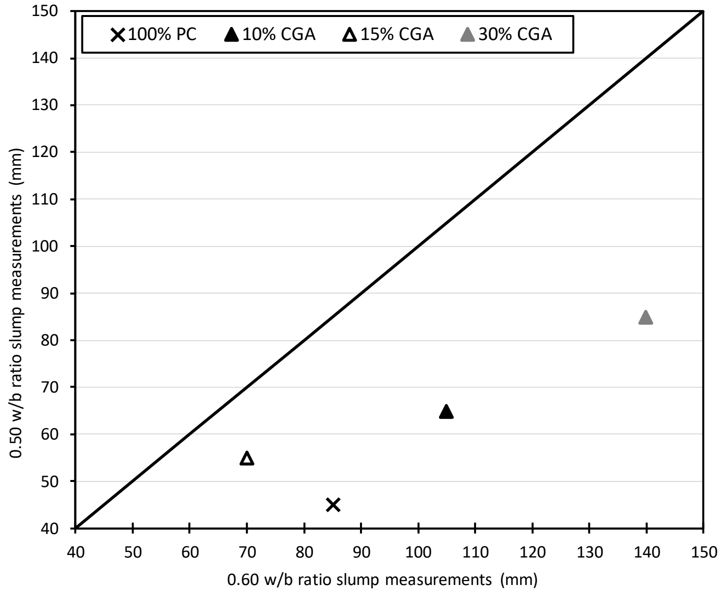

Figure 22: Influence of w/b ratio on the slump measurements of CGA

### 4.2.2 Influence of binder type on slump measurements

The slump measurement of the 10% FA-0.50 concrete was lower than that of the 100% PC-0.50 concrete. The other concrete blends with 0.50 w/b ratio had slump measurements that were higher than those of 10% FA-0.50 and 100% PC-0.50 (see Figure 23). The 100% PC-0.60 and 10% FA-0.60 concretes had the same slump measurements. The slump measurements of the 15% FA-0.60 and 30% FA-0.60 concretes were higher than those of the 100% PC-0.60 and 10% FA-0.60 concretes. The 10% WFA-0.60, 30% WFA-0.60 and 15% CGA-0.60 concretes had slump measurements lower that of the 100% PC-0.60 concrete, while the 10% CGA-0.60, 15% FA-0.60, 15% WFA-0.60, 30% FA-0.60 and 30% CGA-0.60 concretes had slump measurements that were higher than that of the 100% PC-0.60 mix.

#### 4.2.2.1 Considering the concrete mixes with the 0.50 w/b ratio

The 30% CGA-0.50 concrete mix had the highest slump measurement. It can also be seen that the 10% CGA-0.50 concrete mix had the second highest slump measurement and was the same as the one observed for the 30% FA-0.50 concrete. At 10% and 30% replacement level for PC, CGA had the highest influence on the concrete slump when compared to 100% PC-0.50. Mahlaba (2006) reported that the CGA particle shapes were mostly irregular with agglomerated particles from finer particles. This was not considered unusual, as the optical and scanning electron microscopy of fly ash particles has shown that they can vary in shape and size; they can be spherical, rounded, irregular, and be angular shaped (Alonso & Wesche, 2005). But, literature highlights that the spherical shape of the FA particles contributes most to the improvement in workability of concrete (Alonso & Wesche, 2005; Grieve, 1991). The lubricated spherical particle shapes can easily glide over each other improving fluidity unlike irregular particle shapes.

In this investigation, the shape of the CGA particle shapes was not confirmed to be irregular. Due to the crushing and milling undertaken to make the CGA particles finer for the fresh concrete, hardened concrete and hardened mortar tests it was regarded as irregular. CGA particles passing through the 70 µm sieve were used. FA passes through the 45 µm sieve. It was interesting to witness that concrete with the 10% and 30% of CGA which had irregular shaped particles and a greater particle size than FA, had the higher slump measurements than FA concrete. At 15% replacement level for PC, the same slump measurements were observed for both the CGA-0.50 and FA-0.50 concrete. When all the CGA concrete mixes are considered, the 15% replacement level for PC appeared to have a lower influence on the concrete slump. Further investigation is required.

#### 4.2.2.1 Considering the concrete mixes with the 0.60 w/b ratio

The 30% CGA-0.60 concrete mix had the highest slump measurement among concrete mixes made with 0.60 w/b ratio. The 15% FA-0.60 concrete mix had the second highest slump measurement while the 100% PC-0.60 and 10% FA-0.60 concrete mixes had the same slump measurements. The addition of 10% FA in the 10% FA-0.60 mix did not improve the concrete workability due to the low percentage of FA replacement in the PC. This observation supports the finding that only plain PC with FA replacement greater than or equal 15% exhibit positive effects on the concrete workability (Zode, 1999). FA has been reported to generally improve the workability of concrete, due to its particle fineness and spherical shape (Owens, 2009; Grieve, 1991; Kruger, 2003). The spherical particle shape of FA improves the workability of concrete as they provide a lubricating effect in the concrete mix (Grieve, 1991; Zode, 1999; American Coal Ash Association, 2003). Mahlaba (2006) reported that the particle shapes of WFA are also spherical in shape, although there are some particles that may agglomerate into irregular shapes. In general, WFA in its original state has the same particle shape as FA (Mahlaba, et al., 2011), but due to the crushing and milling process to achieve a particle size of 70 µm, the majority of the particle shapes may be altered and become irregular. Observation of the binder particles using optical and scanning electron microscopy were not carried out. Hence it cannot be verified if a change in the particle shapes is responsible for the variation in the concrete slump measurements. There was however a noticeable similarity in the workability of FA-0.60 and WFA-0.60 in the 10%, 15% and 30% PC replacement even though their particle shapes and sizes were different. When comparing FA-0.60 and WFA-0.60 to 100% PC-0.60, at 10% PC replacement, there was no positive change in the concrete workability, however, at 15% the concrete workability increased while it decreased at 30% PC replacement.

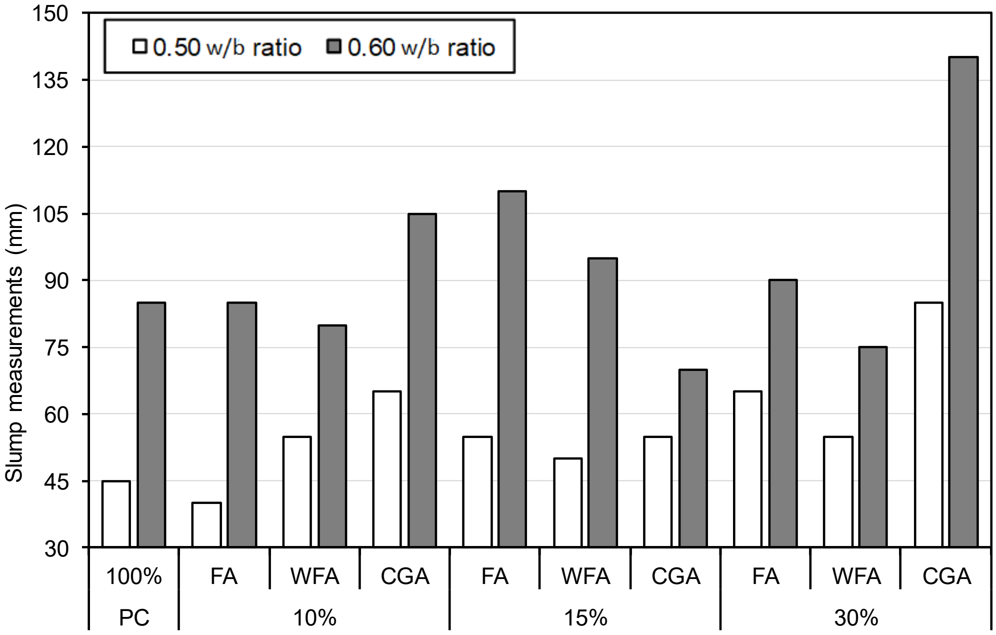

Figure 23: Influence of binder types on the slump measurements

### 4.2.3 Influence of PC replacement level on slump measurements

Only the FA-0.50 concrete mix showed a trend of increasing slump measurements with increasing replacement level for PC. The slump values of the WFA-0.50, CGA-0.50, and CGA-0.60reduced from 10% replacement level for PC to 15%, and then increase from 15% replacement level for PC to 30%. On the other hand, the measured slump of the FA-0.60 and WFA-0.60 concrete, increased from 10% replacement level for PC to 15%, and then decreased from 15% replacement level for PC to 30%. Figure 24 gives a summary of the discussion above.

#### 4.2.3.1 Fly ash

The concrete slump value was expected to increase with an increase in PC replacement with FA (Berg & Kukko, 2005; Dijk, 1987; Kruger, 2003). In this study, only the FA-0.50 slump measurements conformed to the expected trend; the slump increased with increasing replacement level for PC. It can also be seen that the slump values of mixes with 15% and 30% FA was positively influenced by the FA content compared to the 100% PC. At 0.60 w/b ratio, the slump measurement of the 15% FA concrete mix peaked above those of 10% FA and 30% FA mixes. The trend in this result is not consistent with what has been previously reported; the workability of FA concrete improves with increasing PC replacement (Zulu, 2017; Berg & Kukko, 2005; Dijk, 1987; Kruger, 2003), Zode (1999) and Aggarwal, et al. (2010) reported that FA concrete usually exhibits improved workability when 15 to 20% of PC is replaced. Ramaswamy, et al ( 2011) observed that there is considerable improvement in workability up to 20% PC replacement, thereafter the rate of workability improvement reduces slightly.This implies that in some cases, low slump measurements may be observed in FA concrete with up to 30% and higher PC replacement .

#### 4.2.3.2 Weathered fly ash

10% WFA-0.50 and 30% WFA-0.50 had the same slump measurements and while 15% WFA was lower by 5 mm. 15% WFA-0.60 had the highest slump measurement, while 30% WFA-0.60 had the lowest slump value. WFA-0.50 mixes had higher slump measurements than that of the 100% PC-0.50 concrete. With regard to the PC-0.60 concrete, the influence of 10% WFA-0.60 and 30% WFA-0.60 on slump measurements was lower. Both WFA-0.60 and FA-0.60 concrete mixes had the highest slump measurements observed at 15% replacement. FA-0.60 and WFA-0.60 mixes exhibited a similar trend; their slump measurements increased as the PC replacement was increased from 10% to 15%. However, the slump value decreased as the PC replacement was increased from 15% to 30%. These outcomes may be due to the similarity in chemical composition of the FA and WFA binders as reported by Mahlaba (2006). Despite the fact that the WFA-0.60 and FA-0.60 exhibited a similar slump value trend, the blends did not have a comparable influence on the slump measurements; 10% WFA-0.60 and 30% WFA-0.60 mixes did not show an improvement in the concrete workability as their workability was lower than that of the 100% PC-0.60. On the other hand, 10% FA-0.60 had the same slump measurement as that of 100% PC-0.60 mix, suggesting that 10% FA had no influence on the workability of the concrete. 30% FA-0.60 had a positive influence on the slump measurement. The negative influence on slump measurements by 10% WFA-0.60 and 30% WFA-0.60 may be due to the difference in particle shape and size. FA is mostly spherically shaped and has a nominal size of 45 µm, while WFA has an irregular shape with a nominal particle of 70 µm.

#### 4.2.3.3. Coal gasification ash

The highest slump measurements were obtained from the 30% CGA-0.50 and 30% CGA-0.60 concrete mixes while the lowest slump measurement was obtained from the 15% CGA concrete mix. With 10% replacement level for PC, high slump values were recorded, the slump however reduced at 15% replacement level for PC and increased when the PC replacement was increased to 30%. The addition of CGA-0.50 had a positive influence on slump measurements when compared to the 100% PC-0.50 concrete mix. The addition of 15% CGA with 0.60 w/b ratio had a negative influence on the slump value of the resulting concrete mix. CGA-0.50 and CGA-0.60 did not exhibit a similar trend as observed in the WFA concrete mix. The CGA concretes were not expected to exhibit similar trends to the FA concretes due to the difference in particle shapes, particle sizes and a greater difference in chemical composition relative to WFA. The 10% CGA and 30% CGA concrete mixes had higher slump measurements than those of 10% FA and 30% FA. The same influence on the measured was noticed in 15% FA-0.50 and 15% CGA-0.50. With the 0.60 w/b ratio the slump value of 15% FA-0.60 increased by 25 mm and that of 15% CGA-0.60 decreased by 15 mm in comparison to the 100% PC-0.60 mix. The slump measurements of the CGA-0.50 mixes were higher than those of FA-0.50 mixes. The lowest (10%) and highest (30%) replacements for PC by CGA-0.60 had the higher slump measurements than 10% WFA-0.60 and 30% WFA-0.60.

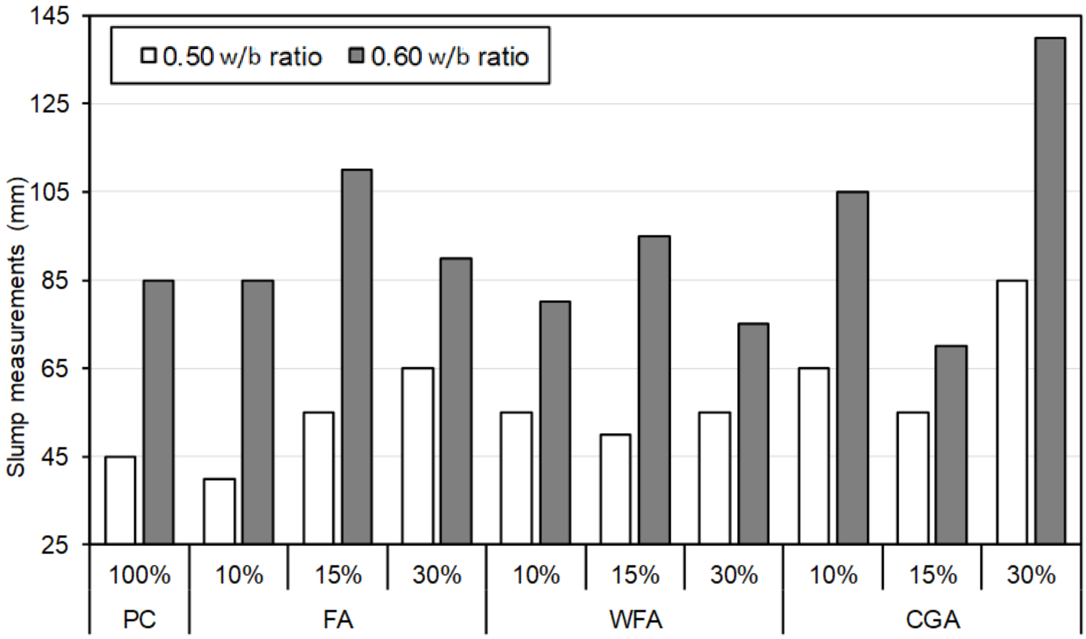

Figure 24: Influence of PC replacement level slump measurements

## 4.3 Compressive Strength

All the compressive strength test results for each cement blend, their corresponding averages and statistical analyses are presented in Appendix B. The bar graphs present the average compressive strength results for each cement blend. The error bars represent the 95% confidence intervals calculated using ANOVA, 4.303 which was used as the t-value with 2 degrees of freedom. The effect of w/b ratio, binder type and percentage of PC replacement on compressive strength at testing ages 7, 28 and 56-days were analysed and are herein presented and discussed.

### 4.3.1 Influence of w/b ratio on compressive strength

Lower compressive strength results were observed for concrete with 0.60 w/b ratio. The 100% PC-0.50 concrete had higher compressive strength than the 100% PC-0.60 concrete (see Figure 25). A higher water-to-binder ratio tends to reduce the concrete compressive strength as the additional water dilutes the concrete mix thereby producing a porous concrete which is susceptible to failure (Alexander, 1998; Babu & Prasad, 2012; Grieve, 2009). It was noted that 100% PC-0.50 and 100% PC-0.60 concrete had the same improvement in compressive strength as the curing days were prolonged. From 7 and 28 days of curing, the compressive strengths of the 100% PC-0.50 and 100% PC-0.60 concrete increased by about 10 MPa, and then between 28-and 56-days of curing, the compressive strengths increased by about 4 MPa. In the FA concrete, the FA-0.50 concrete had higher compressive strength than the FA-0.60 mix (see Figure 26). There was a decrease in the compressive strength development for both FA-0.50 and FA-0.60 concrete, with increasing PC replacement( see Appendix B).

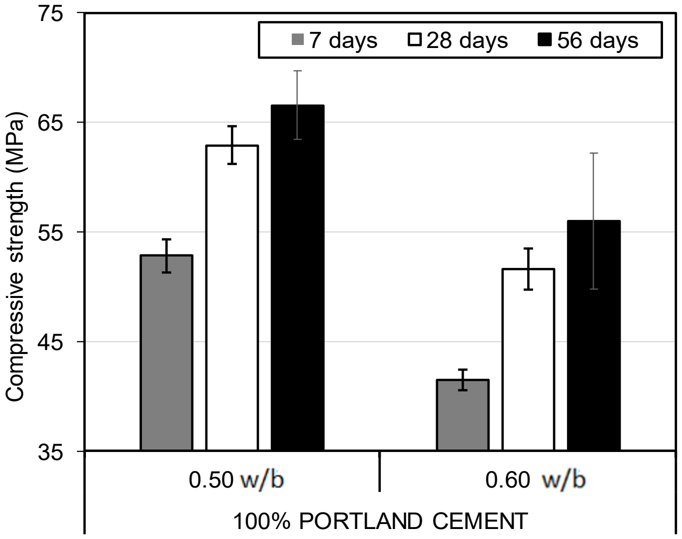

Figure 25: Influence of water-to-binder ratio on the compressive strength of 100% PC concrete

There was a decrease in the compressive strength gain for both WFA-0.50 and WFA-0.60 concrete with increasing PC replacement (see Figure 27). The 56-days compressive strengths of the WFA concretes were lower than the 28-days strengths with an exception of the 30% WFA-0.60 concrete. The cause for the loss of strength could not be determined. Further investigation is required into the chemical reactions of WFA in concrete. It was also observed that with the higher water-cement ratio of 0.60 w/b ratio and a 30% replacement level for PC, the compressive strength of 30% WFA-0.60 increased with a corresponding increase in curing age, conforming to the FA trends observed in literature (Owens, 2009; Lamond, 2006).

The 15% CGA-0.50 and 30% CGA-0.50 concretes had higher compressive strengths than those of 15% CGA-0.50 and 30% CGA-0.60 (Figure 28), respectively. Compressive strength retardation was observed for both CGA-0.50 and CGA-0.60 concrete with increasing PC replacement (see Appendix B). The observed compressive results for 10% CGA-0.50 and 10% CGA-0.60 were unexpected; the 7-days compressive strength of the 10% CGA-0.50 was higher than the 28- and 56-days strength. The 28- and 56-days compressive strength of the 10% CGA-0.60 were the same. These two observations were not witnessed during the literature review (Owens, 2009; Raheem, et al., 2013; James, et al., 2011).

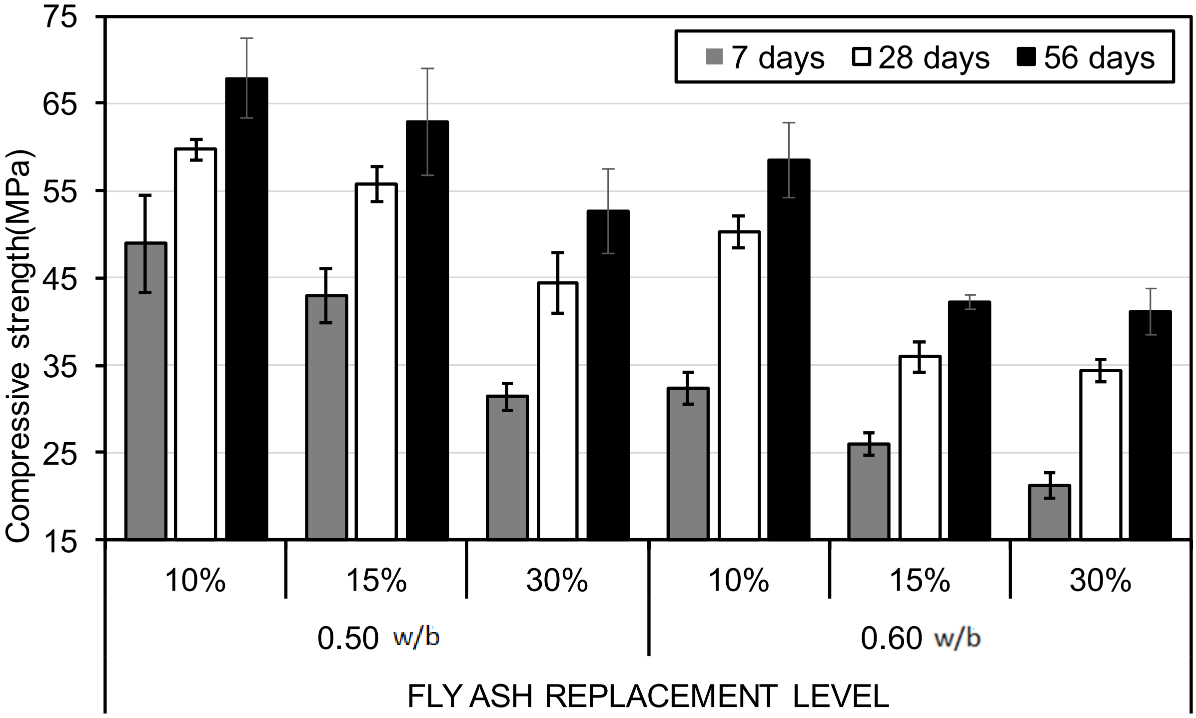

Figure 26: Influence of water-to-binder ratio on the compressive strength of FA concrete

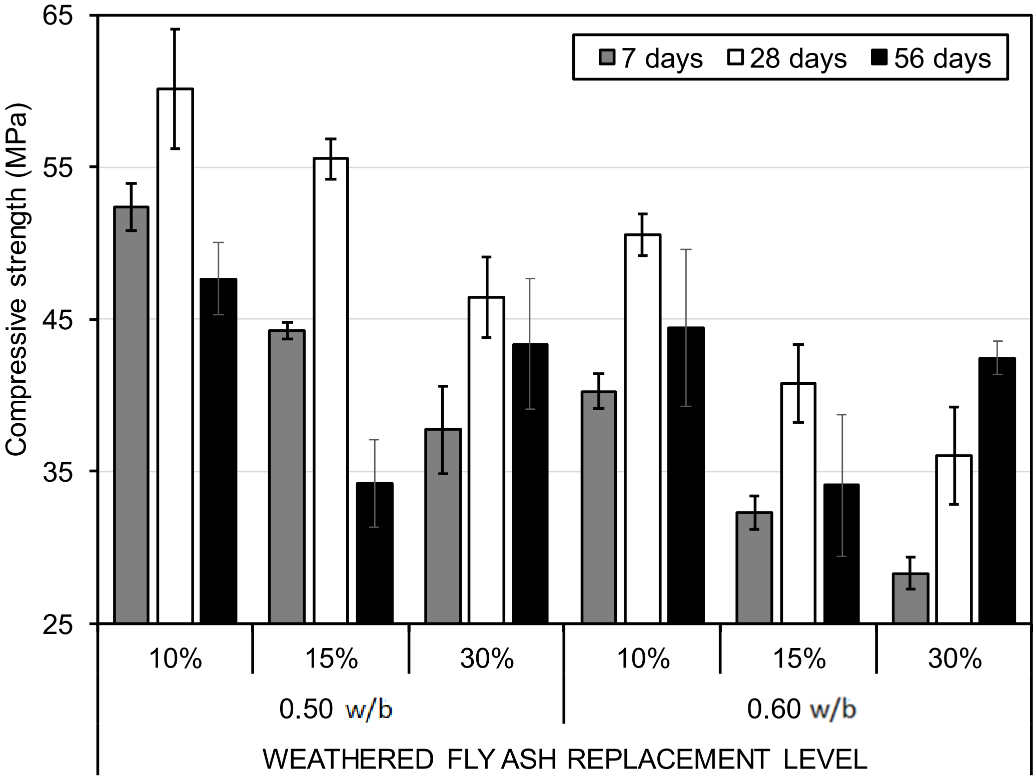

Figure 27: Influence of water-to-binder on the compressive strength of WFA concrete

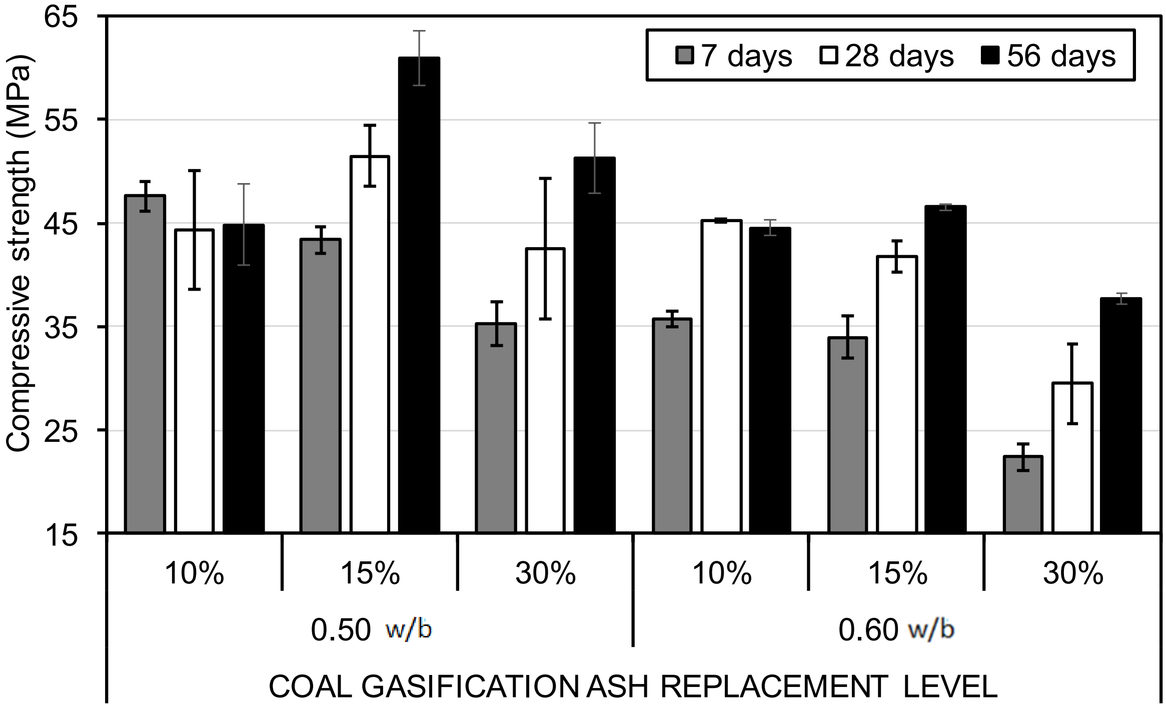

Figure 28: Influence of water-to-binder on the compressive strength of CGA concrete

### 4.3.2 Influence of binder type on compressive strength

The compressive strengths of the 10% WFA-0.50, 10% CGA-0.50, 15% WFA-0.50 and 30% WFA-0.50 concretes did not increase with time, as shown in Figure 29. On the contrary, the 56-days compressive strengths of the 10% WFA-0.50, 15% WFA-0.50 and 30% WFA-0.50 concretes were lower than their observed 28-days strengths. The 7-days compressive strengths of the 10% CGA-0.50 concrete was greater than that observed at 28 and 56-days of testing. The 100% PC-0.50 concrete had the highest compressive strength at 7 and 28-days after moist curing in water. Lastly, the highest compressive was obtained in the 10% FA-0.50 concrete at a test age of 56 days.

#### 4.3.2.1 7-days of compressive strength testing (w/b = 0.50)

The 10% replacement level for PC by FA, WFA and CGA binders had more influence on the concrete compressive strength than the 15% and 30% PC replacement. There was more (90%) cementitious material available for the hydration process in the concrete with 10% replacement level for PC. The difference in compressive strengths between 100% PC-0.50 and 10% FA-0.50 was 4 MPa, between 100% PC-0.50 and 10% WFA-0.50 was 1 MPa and lastly between 100% PC-0.50 and 10% CGA-0.50 it was 5 MPa. The compressive strength of 30% FA-0.50 concrete was 41.5% lower than that of 100% PC-0.50 concrete. The early-age compressive strengths of the WFA-0.50 and CGA-0.50 concrete decreased with increasing PC replacement, like FA-0.50 concrete. The addition of FA seems to retard the strength development in comparison to the 100% PC concrete (Owens, 2009). There was no significant difference in the compressive strength of the 10% FA-0.50 and 100% PC-0.50 concretes as well as 10% WFA-0.50 and 100% PC-0.50 concretes. There was a significant difference in the compressive strength of the 30% WFA-0.50 and 30% FA-0.50 concrete. The same trend was also observed in the 30% CGA-0.50 and 30% FA-0.50 concrete. A detailed outline of the compressive strength and other statistical information in relation to it are provided in Appendix B.

#### 4.3.2.2 28-days of compressive strength testing (w/b = 0.50)

At 28-days of strength testing, the compressive strength of the 10% CGA-0.50 concrete did not develop beyond its 7-days strength. The compressive strength was 4 MPa less. This outcome was only witnessed in the 10% CGA-0.50 concrete. Looking at the compressive strengths in Figure 29, it was assumed that 10% CGA-0.50 concrete had under gone the hydration process, as there was no significant difference between the compressive strengths of the 10% CGA-0.50 and 10% FA-0.50 concrete. According to literature the hydration process takes place immediately when cementitious material encounters water (Grieve, 2009; Perrie, 2009; Addis & Goodman, 2009). The hydration process releases $Ca(OH)_2$ to enable the pozzolanic activity in SCM concretes, which had lied dormant for 3 to 7 days. 10% CGA-0.50 seems to have an issue with the pozzolanic activity at 28-days of testing. The lack of strength development may be due to the chemical and mineralogical composition of CGA, and reactivity with the released $Ca(OH)_2$. McCarter & Tran (1996) reported that after the dormant stage a rapid activity takes place with the calcium hydroxide, but Mehta (1986) reported that the pozzolanic reaction is slow so that the rates of both heat liberation and strength development are correspondingly slow. In this case, it seems 10% CGA-0.50 is undergoing a slow pozzolanic activity. The pozzolanic activity in CGA concrete may require a replacement level for PC greater than 10% to influence the development of the compressive strength, see Figure 29 CGA concrete with higher replacement levels for PC did not have their 28-days compressive strengths less than their 7-days strength. In the concrete mixes, the 10% replacement level for PC in the FA-0.50 and WFA-0.50 mixes had more influence on the concrete compressive strength, however, the compressive strength of the 10% FA-0.50 concrete was less than that of the 100% PC-0.50 by 3 MPa and less than that of 10% WFA-0.50 by 4 MPa. The compressive strength of the 15% FA-0.50 and 15% WFA-0.50 were the same. The FA-0.50 and WFA-0.50 concretes had nearly equal compressive strengths (Appendix B). The non-disparity in the compressive strengths of the WFA and FA concretes is likely due to their similar chemical composition (Mahlaba, 2006; Matjie, et al., 2005). Lastly, there was no significant difference between the compressive strengths of the 100% PC-0.50 and 10% WFA-0.50 concretes. With the SCM, there was no significant difference between the 10% FA-0.50 and 10% WFA-0.50 concretes, Appendix B presents the statistical information.

#### 4.3.2.3 56-days of compressive strength testing (w/b = 0.50)

The compressive strength of the 10% FA-0.50 concrete (after 56-days of curing in water ) was almost the same with that of 100% PC-0.50 concrete. The later age compressive strength development of FA concrete beyond that of plain PC concrete has also been reported by other authors (Harison, et al., 2014; Rahul Upadhyay, 2014; Nagabhushana, 2015).

The 56-days compressive strengths of 10% WFA-0.50, 10% CGA-0.50 and 15% WFA-0.50 concretes did not increase beyond the observed 28-days of strength. Seeing as the compressive strength of 10% CGA-0.50 at 56-days was the same as that at 28-days, the same assumptions are held, that there may be a low reactivity between CGA-0.50 and $Ca(OH)_2$, there needs to be an understanding of the mineralogical and chemical composition and CGA is more reactive with a replacement level for PC greater than 10%. The same reasoning cannot be used for all WFA-0.50 concrete. The compressive strength of the 15% WFA-0.50

concrete is extremely low and significantly different from the 7-days strengths of 15% FA-0.50 and 15% WFA-0.50 concretes. An investigation into the mineralogical and chemical composition of WFA is required, literature on WFA as a supplementary cementitious material or FA with a similar trend was not found hence there is no documentary evidence.

There was no significant difference in the compressive strengths of the following concrete mixes; 100% PC-0.50 and 10% FA-0.50, as well as 100% PC-0.50 and 15% CGA-0.50. There was also no significant difference in the 56-day compressive strengths of the 10% FA-0.50 and 10% WFA, and 10% FA-0.50 and 15% CGA-0.50. A detailed outline of the compressive strength and other statistical information in relation to it are provided in Appendix B.

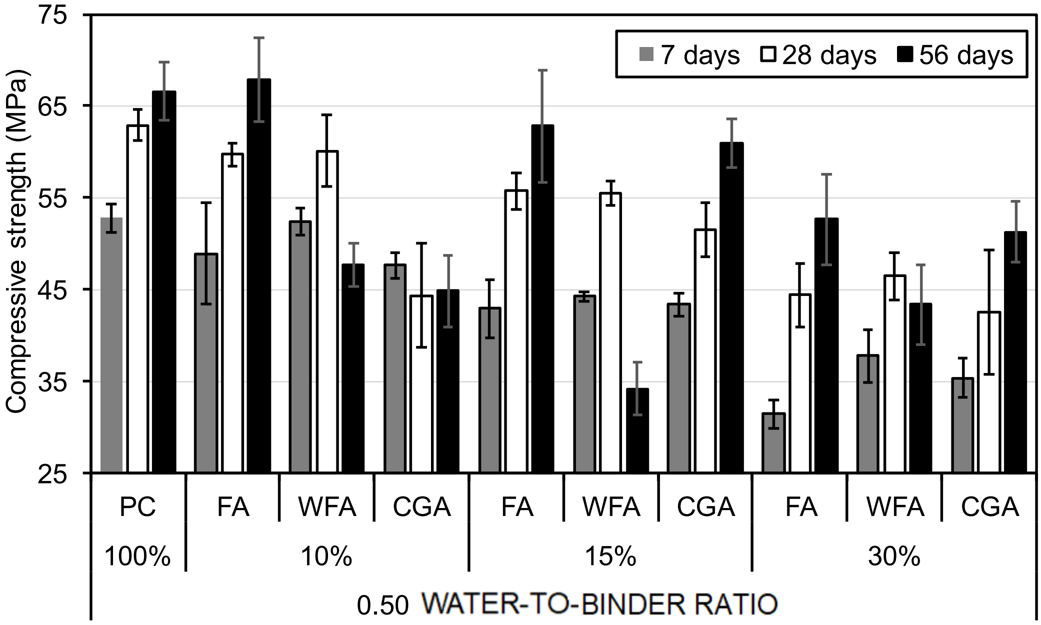

Figure 29: Influence of binder type on compressive strength of concrete with 0.50 w/b ratio

The compressive strengths of 10% WFA-0.60 and 15% WFA-0.60 did not increase with age, as shown in Figure 30. The 56-days compressive strengths of 10% WFA-0.60 and 15% WFA-0.60 were lower than those observed at 28-days of testing. The 100% PC-0.60 concrete had the highest compressive strengths at 7 and 28-days of testing while the 10% FA-0.60 had the highest 56-days compressive strength. The 30% FA-0.60, 30% WFA and 30% CGA concretes were observed to have closely related compressive strength results and trends.

#### 4.3.2.4 7-days of compressive strength testing (w/b = 0.60)

The concretes with 10% replacement level for PC had more influence on the compressive strength values than those with 15% and 30% replacement level for PC. The compressive strengths of the 10% FA-0.60, 10% WFA-0.60 and 10% CGA-0.60 concretes were lower that of 100% PC-0.60 but not very different, the differences are as follows; 9 MPa, 1 MPa and 5 MPa, respectively. The 30% FA-0.60 concrete had a compressive strength which was 48.8% lower than that of 100% PC-0.60. The early-age strengths of the WFA-0.60 and CGA-0.60 concretes decreased as the replacement level for PC was increased (e.g. for FA). The addition of FA to the PC reduced the concretes early strength in comparison to the 100% PC concrete (Owens, 2009). There was no significant difference in the compressive strengths of the 100% PC-0.60 and 10% WFA-0.60, as well as 30% FA-0.60 and 30% CGA-0.60 concretes. Appendix B presents the compressive strengths and other relevant statistical information.

#### 4.3.2.5 28-days of compressive strength testing (w/b = 0.60)

At this test age, compressive strengths of the FA and WFA concretes with 10% PC-0.60 replacement were influenced the most. Similar compressive strengths were obtained for the 10% FA-0.60, 10% WFA-0.60, and 100% PC-0.60 concretes. A similarity in the compressive strengths of the FA-0.60 and WFA-0.60 concretes was observed in the concrete with 10% replacement level for PC. The FA-0.60 concretes had lower compressive strengths compared to those of the WFA-0.60 concretes with 15% and 30% replacement level for PC. This suggests that the addition of WFA-0.60 had a higher influence on the concrete compressive strength compared to FA-0.60. On the other hand, no significant difference was observed in the 100% PC-0.60 and 10% FA-0.60, 100% PC-0.60 and 10% WFA-0.60, 30% FA-0.60 and 30% WFA-0.60, 30% FA-0.60 and 30% CGA-0.60 concretes.

#### 4.3.2.6 56-days of compressive strength testing (w/b = 0.60)

At 56-days, the compressive strength of the 10% FA-0.60 concrete exceeded that of the 100% PC-0.60 concrete by 3 MPa. Hence the addition of the 10% FA improved the concrete compressive strength (Harison, et al., 2014; Rahul Upadhyay, 2014; Nagabhushana, 2015). Considering the 10% WFA-0.60, 10% CGA-0.60 and 15% WFA-0.60 concretes, their compressive strengths did not increase beyond the 28-days strength. was Although this trend may not be fully understood and explained, this result is consistent with what that which was obtained for the 0.50 w/b ratio, Figure 29. As earlier stated, no literature was available in which WFA-0.60 and CGA-0.60 had been used as supplementary cementitious materials. Further investigation is required on the suitability of WFA and CGA as supplementary cementitious materials. There was no significant difference between the compressive strengths of the 100% PC-0.60 and 10% FA-0.60, 30% FA-0.60 and 30% WFA-0.60, 30% FA-0.60 and 30% CGA-0.60 concretes.

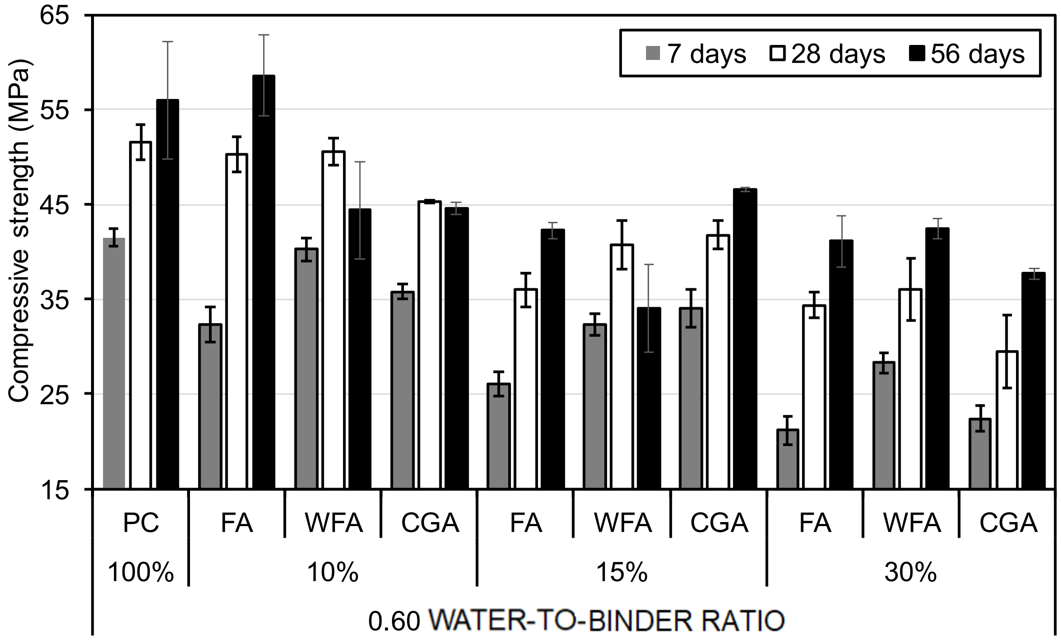

Figure 30: Influence of binder type on compressive strength of concrete with 0.60 w/b ratio

### 4.3.3 Influence of replacement level on compressive strength

In general, the early-age strengths of the FA-0.50, WFA-0.50, and CGA-0.50 concretes decreased with increasing replacement for PC (see Figure 31). The SCMs (FA, WFA and CGA)-0.50 had lower 7 and 28-days compressive strengths compared to the 100% PC-0.50 concrete. However, the 56-days compressive strengths of the 10% FA-0.50 concrete was higher than that of the 100% PC-0.50 concrete. The 56-days compressive strengths of the concretes with WFA-0.50 at 10%, 15% and 30% replacement levels for PC was lower than those at 28-days of testing. An explanation to this trend may be tenable by studying the hydration process and pozzolanic activity of this concrete.

#### 4.3.3.1 Fly ash (w/b=0.50)

A 10% replacement of PC with FA-0.50 improved the concretes compressive strength, although the 7-days compressive strength of the FA-0.50 concrete reduced as the PC replacement was increased. The strength reduction in this FA-0.50 concrete is influenced by the hydration process and its pozzolanic activity. According to literature the pozzolanic activity is only activated 3 to 7 days after the concrete is cast, at this instance $Ca(OH)_2$ released from the hydration process is used to start the pozzolanic reaction in the FA (McCarter & Tran, 1996). If the FA content is increased, more time is required for all the pozzolans to participate in the strength development of concrete (Wang, et al., 2004). The compressive strength development at 7 and 28-days for the 10% FA-0.50, 15% FA-0.50 and 30% FA-0.50 concretes were related; 11 MPa, 13 MPa and 13 MPa, respectively. The compressive strength development at 28 and 56 days for the 10% FA-0.50, 15% FA-0.50 and 30% FA-0.50 were also related; 7 MPa, 8 MPa and 9 MPa, respectively. Studies have shown that the pozzolanic reaction of FA is effective up to 90 days and beyond after the concrete is cast, the mechanical and durability properties of this concrete also show considerable improvement (Zulu, 2017).

#### 4.3.3.2 Weathered fly ash (w/b=0.50)

At 56-days of testing, the 10% WFA-0.50, 15% WFA-0.50 and 30% WFA-0.50 concretes did not attain a higher compressive strength than that of the 100% PC-0.50 concrete. The compressive strengths of the WFA concretes at 56-days of testing did not increase, and the observed results were not comparable with that of the FA concretes. Due to the similarity in the chemical composition of WFA and FA binders, they were expected to have comparable results to FA concretes. The similarity in chemical composition of the FA and WFA used in this study was confirmed using the X-ray fluorescence (XRF) test. The XRF result is presented in Appendix I. A contributing factor to the observed results was the difference in the particle size of the binders. It has been reported that particle sizes that are retained in the 0.300 mm sieve are considered inert as they do not participate in the pozzolanic reactions which occur in the concrete. Conversely, particles which pass the 0.010 mm and the 0.300 mm sieves have been reported to slowly react (Heyns & Hassan, 2014; Zulu, 2017). In this investigation, the FA has a particle size of 0.450 mm while the WFA is 0.700 mm, both the FA and WFA have particle sizes that are greater than 0.300mm, hence the WFA would be considered more inert than the FA. Further studies on the influence of WFA particle sizes on the compressive strengths of concrete needs to be undertaken.

#### 4.3.3.3 Coal gasification ash (w/b=0.50)

In this concrete, the 15% PC replacement with CGA-0.50 had the highest influence on the compressive strength. The 7-day compressive strengths of the CGA-0.50 concretes reduced with increasing PC replacement. Therefore, CGA-0.50 concrete like FA-0.50 concrete can be assumed that the pozzolanic activity of CGA will remain dormant for 3 to 7 days, until $Ca(OH)_2$ is released from the PC hydration process (McCarter & Tran, 1996). The 7 to 28-days strength development in the 15% CGA-0.50 and 30% CGA-0.50 concretes was the same; 8 MPa, while the 28 to 56-days strength development of the 15% CGA-0.50 concrete increased by 10 MPa, and the 30% CGA-0.50 concrete strength also increased by 8 MPa. The 56-days compressive strengths of the 15% CGA-0.50 and 30% CGA-0.50 concretes were comparable to those of the 15% FA-0.50 and 30% FA-0.50 concretes. An investigation into the long-term compressive strength development of CGA would assist to determine if its 90-day strength and beyond, will increase in a similar manner with that of other commonly used pozzolanas such as FA.

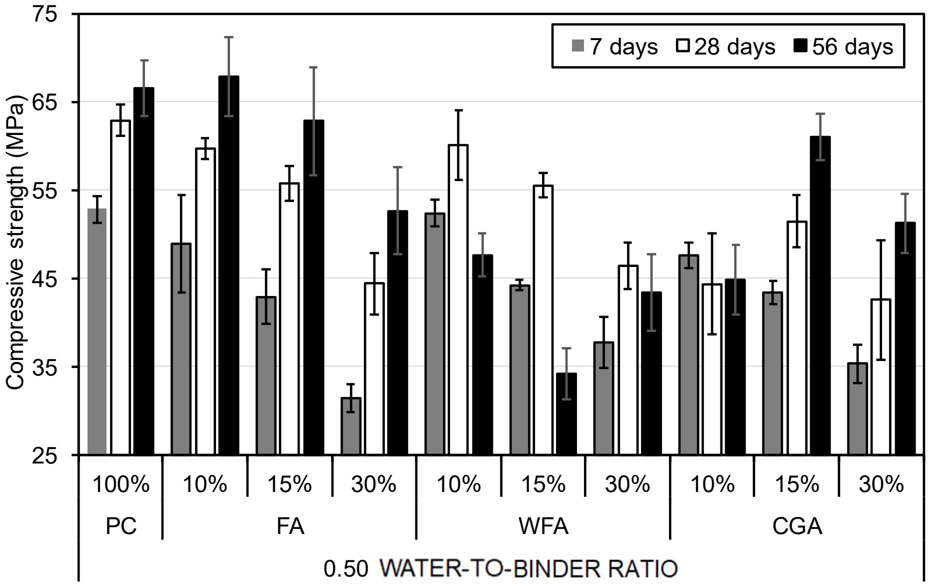

Figure 31: Influence of replacement level on the compressive strength of concrete with 0.50 w/b ratio

The early age strength of the SCM-0.60 concretes decreased with increasing PC replacement (see Figure 32). The value of the 28-days compressive strengths of the 10% FA-0.60 and 10% WFA-0.60 concretes were close to that of the 100% PC-0.60. The 56-days compressive strength of the 10% FA-0.60 concrete was higher than that of the 100% PC-0.60 concrete at the same age. In the concrete made by replacing 10% and 15% of PC with WFA, the 56-days compressive strengths were lower than those obtained at 28-days of testing. This trend was also observed in the 10% PC replacement with CGA.

#### 4.3.3.4 Fly ash (w/b=0.60)

A 10% replacement level for PC with FA-0.60 improved the concrete compressive strength. The 7-days compressive strengths of the FA-0.60 concrete was reduced as the PC replacement was increased. The strength reduction in this concrete is related to the hydration process and pozzolanic activity of the FA. If the FA content is increased, its pozzolanic reaction will be slowed because the quantity of $Ca(OH)_2$ produced will also be reduced, hence the concrete strength will be reduced (Wang, et al., 2004). The 7 and 28-days compressive strength development of the 10% FA-0.60 concrete was higher than that of the 15% FA-0.60 and 30% FA-0.60 concretes.

#### 4.3.3.5 Weathered fly ash (w/b=0.60)

At 56-days of testing, the 10% WFA-0.60, 15% WFA-0.60 and 30% WFA-0.60 concretes did not attain a compressive strength that exceeded that of the 100% PC-0.60 concrete. The compressive strengths of the 10% WFA-0.60 and 15% WFA-0.60 concretes did not increase after the 28-days strength was determined, and the results obtained were not comparable with that of the FA concretes. Due to the similarity in chemical composition FA-0.60 and WFA-0.60 concretes, were expected to have similar compressive strength results. The similarities in chemical compositions were confirmed using the X-ray fluorescence (XRF) tests, captured in Appendix I. Further studies into the influence of WFA particle sizes on the compressive strength of concrete need to be carried out.

#### 4.3.3.6 Coal gasification ash (w/b=0.60)

The 15% CGA-0.60 concrete had the highest influence on the concrete compressive strength. The 7-days compressive strength of the CGA concretes reduced with increasing PC replacement . But the 7-days compressive strength of the 10% CGA-0.60, 15% CGA-0.60 and 30% CGA-0.60 concretes were greater than those of 10% FA-0.60, 15% FA-0.60 and 30% FA-0.60 concrete. At 28-days the compressive strength of the 15% CGA-0.60 concrete was greater than that of the 15% FA-0.60 concrete.

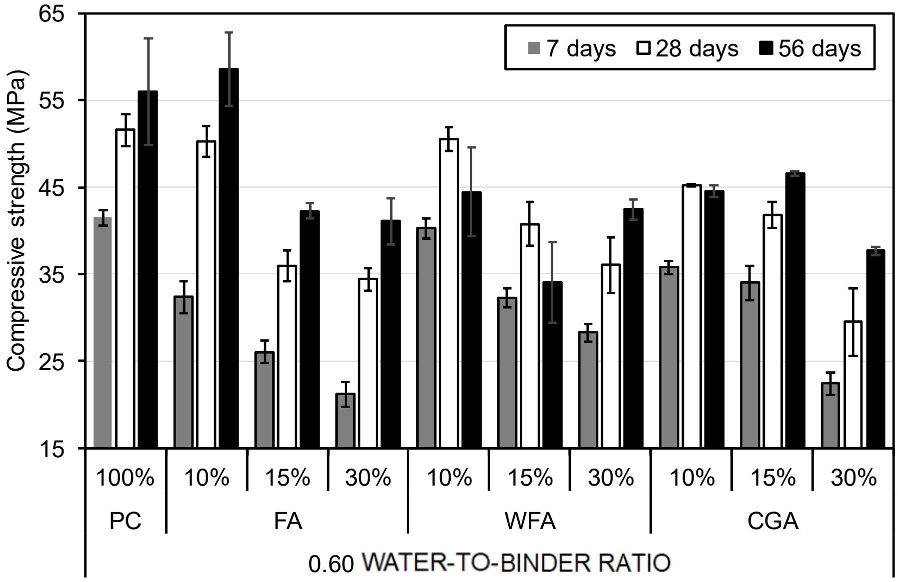

Figure 32: Influence of replacement level on the compressive strength of concrete with 0.60 w/b ratio

## 4.4 Tensile Splitting Strength

All the tensile strength test results for each cement blend, their corresponding averages and their statistical analysis are presented in Appendix C. The bar graphs present the average tensile strength results for each cement blend. The error bars represent the 95% confidence intervals calculated using ANOVA, 4.303 was used as the t-value with 2 degrees of freedom.

The effect of w/b ratio, binder type and percentage replacement of PC on tensile strength at a testing age 28-days were analysed.

### 4.4.1 Influence of w/b ratio on tensile splitting strength

There was a noticeable difference between the observed tensile strengths of the SCM concretes and 100% PC concretes of the same w/b ratio. The tensile strength of 100% PC-0.50 was lower than that of the SCM-0.50 concretes, whereas the tensile strength of 100% PC-0.60 was higher than the tensile strength of the SCM-0.60 concretes. The tensile strength of the 100% PC-0.60 concrete was 11.9% higher than that of 100% PC-0.50 concrete (see Figure 33). Concrete has a low tensile strength which results into cracks (Illston & Domone, 2001). It was expected that the tensile splitting strength would reduce with increasing w/b ratio. Abel & Hover (1998) conducted tensile tests on concrete mixes with water-to-binder ratios varying from 0.30 to 0.70, they found that higher tensile strength values were obtained for the concrete with low w/b ratios.

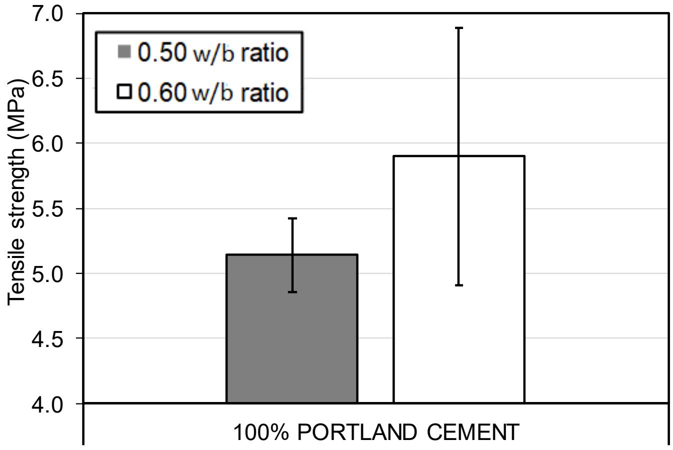

Figure 33: Influence of water-to-binder ratio on the tensile splitting strength 100% Portland concrete

Higher tensile strengths were recorded in FA-0.50 concretes, this result was expected, since a concrete with higher w/b ratio will be weaker due to formation of pores in the concrete as a results of the presence of excess water in the mix (Dippenaar, 2015). Figure 34 illustrates that increasing the PC replacement and w/b ratio decreases the tensile strength (FA-0.50 and FA-0.60) of concrete.

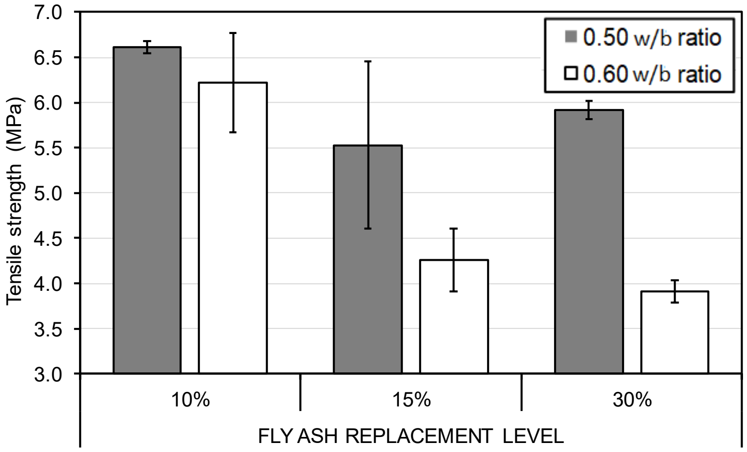

Figure 34: Influence of the water-to-binder ratio on the tensile splitting strength of concrete FA concrete

The WFA concrete with the lower w/b ratio also had higher tensile strength, however, the tensile increased with increasing PC replacement in the mix with 0.60 w/b ratio. Figure 35 illustrates that the highest tensile strengths were obtained in the 15% WFA-0.50 and 15% WFA-0.60 concretes. A clear overlap of the tensile strength results with 95% confidence level was however not observed in the 10% WFA, 15% WFA and 30% WFA concretes.

The CGA concrete with the lower w/b ratio had higher tensile strengths compared to concretes which had the higher w/b ratio. Figure 36 shows that 30% CGA-0.50 and 30% CGA-0.60 concretes had the highest tensile strengths, for their corresponding w/b ratios.

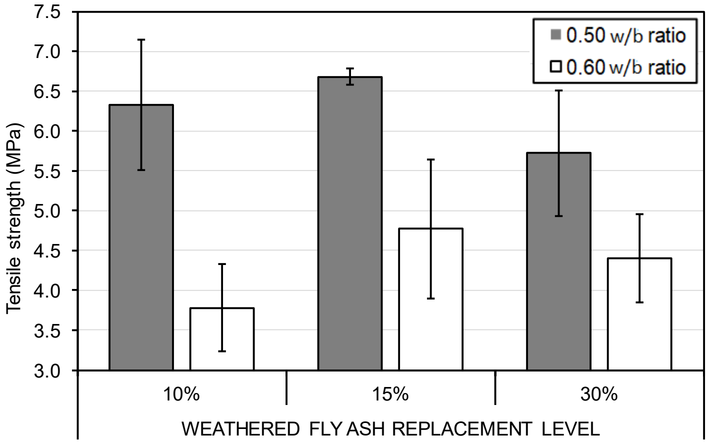

Figure 35: Influence of the water-to-binder ratio on the tensile splitting strength of concrete WFA concrete

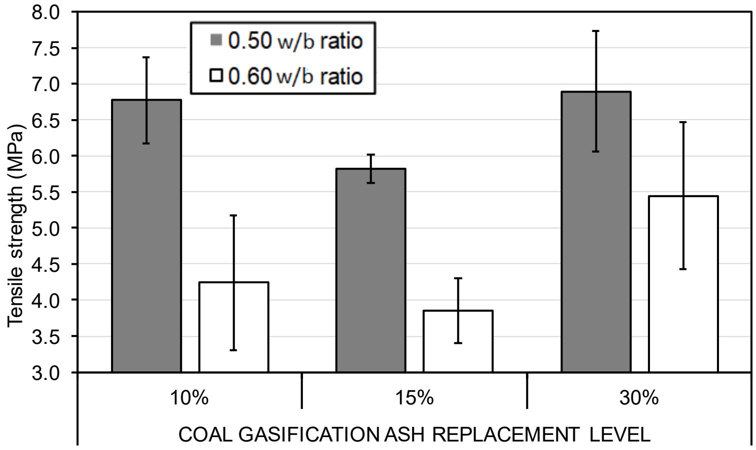

Figure 36: Influence of the water-to-binder ratio on the tensile splitting strength of concrete CGA concrete

### 4.4.2 Influence of binder type on tensile splitting strength

The tensile strengths of all SCM-0.50 concretes were greater than that observed for 100% PC-0.50. The tensile strength of the 10% FA-0.60 concrete was greater than that of the 100% PC-0.60 concrete (see Figure 37).

#### 4.4.2.1 0.50 water-to-binder ratio

All the SCM-0.50 concretes had a positive influence on the concrete tensile strength. The tensile strength of the 10% FA-0.50 concrete was higher than that of the 100% PC-0.50 concrete by 1.5 MPa, while the tensile strength of the 10% CGA concrete was 0.2 MPa higher than that of the 10% FA-0.50 concrete. The tensile strength of the 30% FA-0.50 concrete was 0.8 MPa higher than that of the 100% PC-0.50 concrete, and the tensile strength of the 30% CGA-0.50 concrete was 1 MPa higher than that of the 30% FA-0.50 concrete. In both cases, the CGA-0.50 concretes had the most positive influence on the concrete tensile strength. There was no statistical significant difference between the tensile strength of the 100% PC-0.50 and 15% FA-0.50 concretes, as well as the 100% PC-0.50 and 30% FA-0.50 concretes (Appendix C). The tensile strength of concrete produced from blended cements is affected by the fineness of the supplementary cementitious material, the percentage of PC replaced, and the moisture content in the concrete. FA concretes were expected to have higher tensile strengths than CGA and WFA concretes based on the particle size distribution of the FA binder.

#### 4.4.2.2 0.60 water-to-binder ratio

Only the tensile strength of the specimen made of 10% FA-0.60 exceeded that of the 100% PC-0.60 concrete (see Figure 37). There was a significant difference between the tensile strengths of the 100% PC-0.60 and SCM-0.60 concretes; 10% WFA-0.60, 10% CGA-0.60,

15% FA-0.60, 15% WFA-0.60, 15% CGA-0.50, 30% FA-0.50 and 30% WFA-0.60 concretes. The 30% replacement level for PC had the highest tensile strengths for 30% WFA and 30 CGA with 0.60 w/b ratio. When looking at Figure 37 it may be deduced that higher replacement levels for PC by WFA, and CGA with 0.60 w/b ratio may improve the tensile strength of concrete.

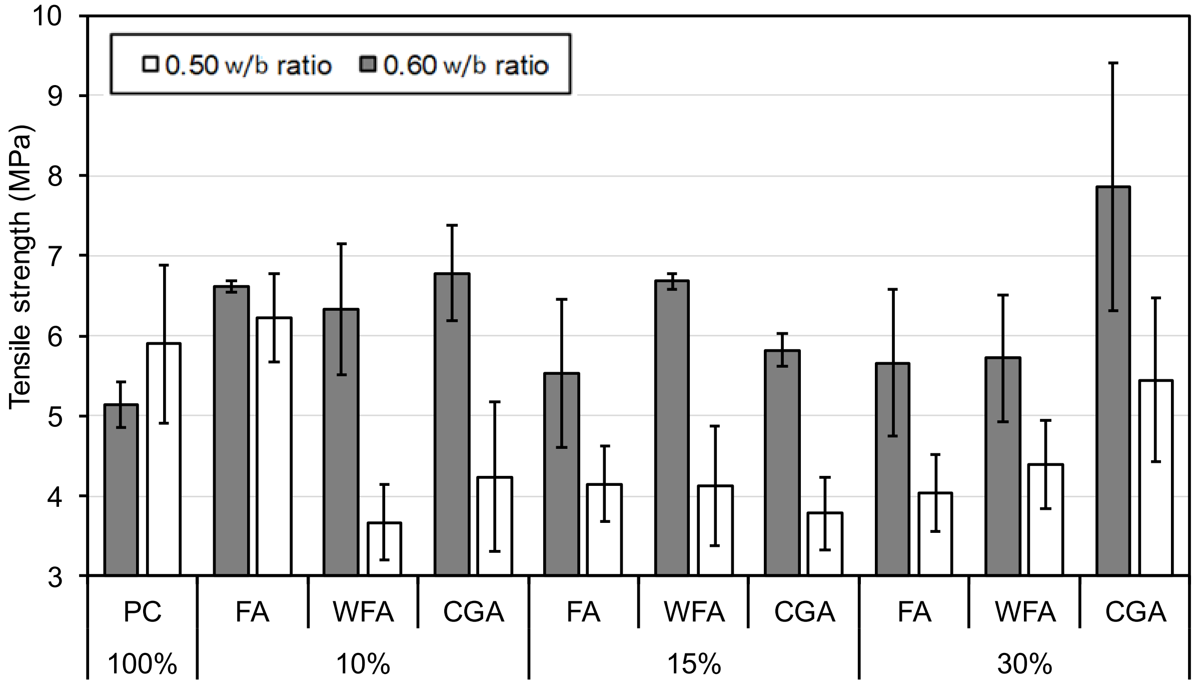

Figure 37: Influence of binder type on the tensile splitting strength on concrete

### 4.4.3 Influence of PC replacement on tensile splitting strength

The tensile strength of the FA-0.60 concretes decreased with increasing PC replacement in the concrete. Previous work done to determine the impact of fly ash percentage on the tensile strength of concrete found that the concrete tensile strength increases with increasing PC replacement with FA (M H Wan Ibrahim, 2015; Maliki, et al., 2017). The 10% FA-0.50 and 10% FA-0.60 concretes had the most influence on the tensile strength for the FA blends. The 15% WFA-0.50 and 30% WFA-0.60 concretes had the most influence on the tensile strength for the WFA blends, while the 30% CGA-0.50 and 30% CGA-0.60 concretes had the most influence on the tensile strength for the CGA blended cement concretes.

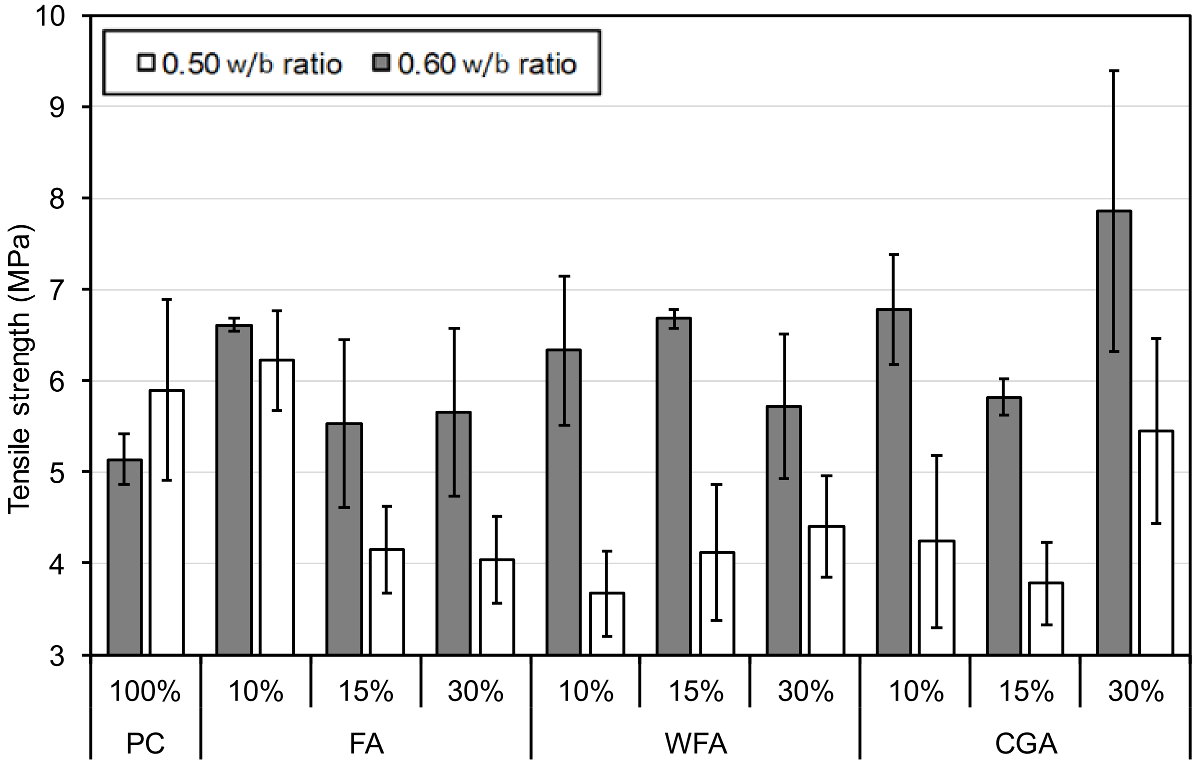

Figure 38: Influence of replacement level on the tensile splitting strength of concrete

## 4.5 Durability Index test results

The three durability index test results for each cement blend, their statistical analyses and additional information are presented in Appendix D to Appendix F. The bar graphs present the average indices for each cement blend. The error bars represent the 95% confidence intervals calculated using ANOVA, 3.182 was used as the t-value with 3 degrees of freedom. During analyses outliers were identified and removed before the data was analysed. The effect of w/b ratio, SCM (binder) type and percentage replacement of PC on durability at 28-days testing age were assessed. The PC/SCM blends are expected to improve the concrete durability by reducing its permeability, porosity and diffusion. The judgement on the quality of concrete in the following analysis is based literature findings (Alexander, et al., 2001; Mukadam, 2014). Alexander, et al (2001) and Mukadam (2014) have categorised the durability index values of concrete from the tests into very poor, poor, good and excellent quality.

### 4.5.1 Oxygen Permeability Index results

The oxygen permeability index test (OPI) was determined by taking the negative logarithm of the coefficient of oxygen permeability (k). The higher OPI values indicate a reduced permeability and better-quality concrete. A lower water-to-binder ratio is expected to provide a less permeable concrete, indicated by high OPI values. The higher the index values, the less permeable (higher quality) the concrete (Ballim *et al.,* 2009).

#### 4.5.1.1 Influence of w/b ratio on oxygen permeability index

There was no clear trend in the 100% PC, FA and CGA concretes when investigating the influence of w/b ratio on the oxygen permeability index values. Some concrete blends with low w/b ratio had high OPI values, whilst the others had low OPI values. Higher OPI values where observed in WFA concretes with 0.60 w/b ratio. The quality of concrete did not improve with age for many of the concretes. There was no difference in the OPI values of 100% PC-0.50 and 100% PC-0.60 at 28-days of testing (Figure 39). It was expected that the concrete made with 0.50 w/b ratio would yield higher OPI values than that of the 0.60 w/b ratio due to an increase in porosity of the concrete as a result of increased capillary porosity within the concrete matrix when higher w/b ratios used (Ballim, et al., 2009; Alexander, 1998).

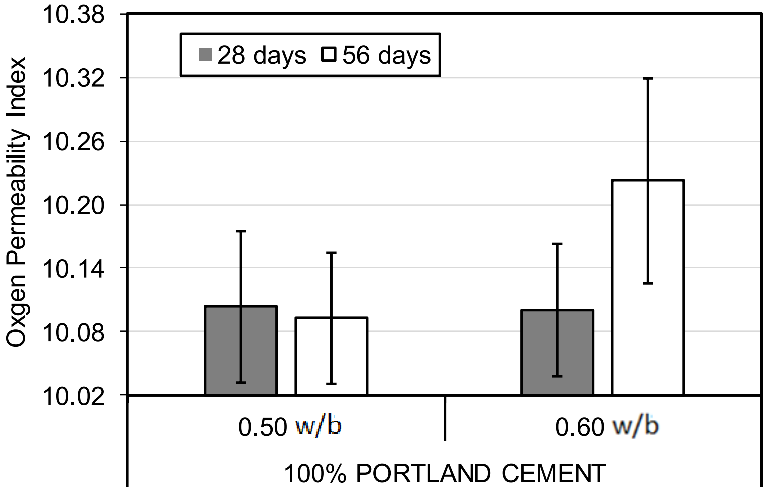

Figure 39: Influence of water-to-binder ratio on the oxygen permeability index results of 100% PC concrete

At 28-days of testing, the 10% FA-0.50 and 30% FA-0.50 concretes had slightly better OPI values than the 10% FA-0.60 and 30% FA-0.60 concretes (see Figure 40). The 15% FA concrete with 0.60 w/b ratio an OPI value 1% higher than that of 15% FA-0.50 concrete. When tested at 56-days, the 10% FA and 30% FA concretes with 0.50 w/b ratio had slightly higher OPI values than those with 0.60 w/b ratio. The 15% FA-0.60 concrete had slightly better quality than 15% FA-0.50 concrete. The 0.50 w/b ratio had more influence on the oxygen permeability index results of FA concretes. There was no improvement in the concrete OPI with age. All FA concrete blends had OPI values above 9.5; this indicated that the concrete is of good quality according to literature (Alexander, et al., 2001; Mukadam, 2014).

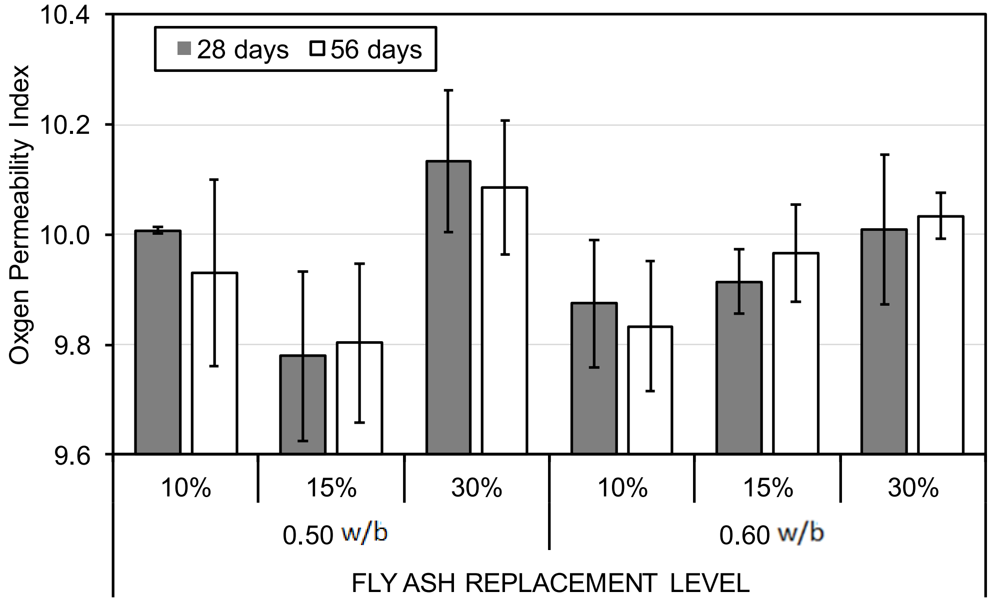

Figure 40: Influence of water-to-binder ratio on the oxygen permeability index results of FA concrete

At 28 and 56-days of testing, higher OPI values were obtained for the WFA-0.60 concretes (see Figure 41). The OPI values of the 15% WFA-0.50, 30% WFA-0.50 and 30% WFA-0.60 concretes did not increase with age. The 0.60 w/b ratio had more influence on the oxygen permeability index results of WFA concretes. All WFA concrete blends had OPI values above 9.5, indicative of good quality concrete (Alexander, et al., 2001; Mukadam, 2014).

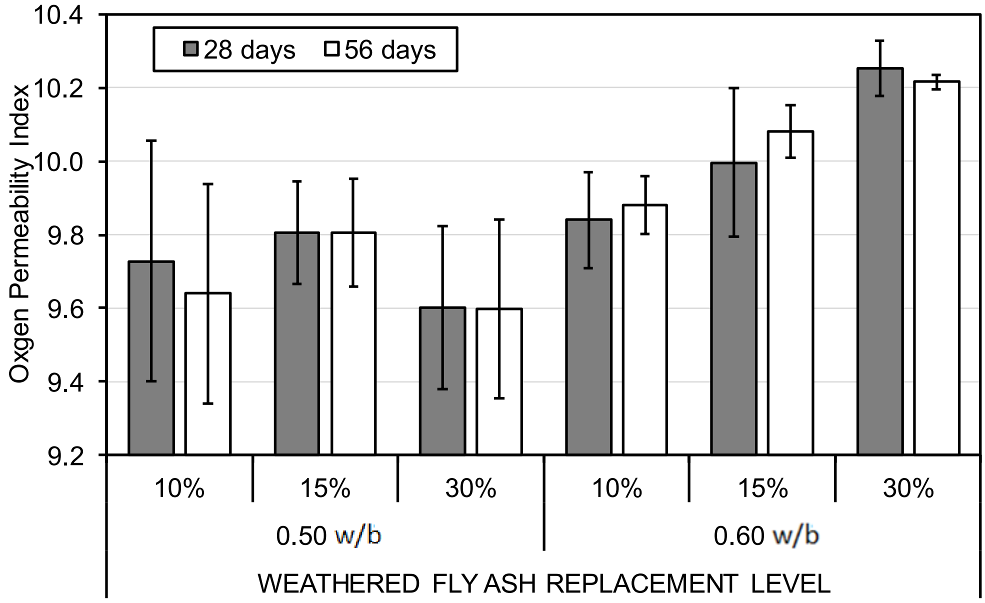

Figure 41: Influence of water-to-binder ratio on the oxygen permeability index results of WFA concrete

At 28-days of testing, the 10% CGA-0.50 and 10% CGA-0.60 had the same influence of on the concrete OPI. The concrete with 15% CGA-0.50 had an OPI value 2.9% higher than the 15% CGA-0.60 concrete, but the 30% CGA-0.50 had and OPI value 4% lower than the 30% CGA-0.60 concrete (see Figure 42). At 56-days of testing, the 15% CGA-0.50 and 30% CGA-0.50 concretes were of better quality than the 15% CGA-0.60 and 30% CGA-0.60 concretes. The 0.60 w/b ratio had more influence on the concrete OPI. The same OPI values were observed for the 10% CGA-0.60, 15% CGA-0.50, 15% CGA-0.60 and 30% CGA-0.60 concretes at 28- and 56-days of testing. Most of the CGA concrete blends had OPI values above 10, this was an indication of excellent quality concrete according to literature (Alexander, et al., 2001; Mukadam, 2014).

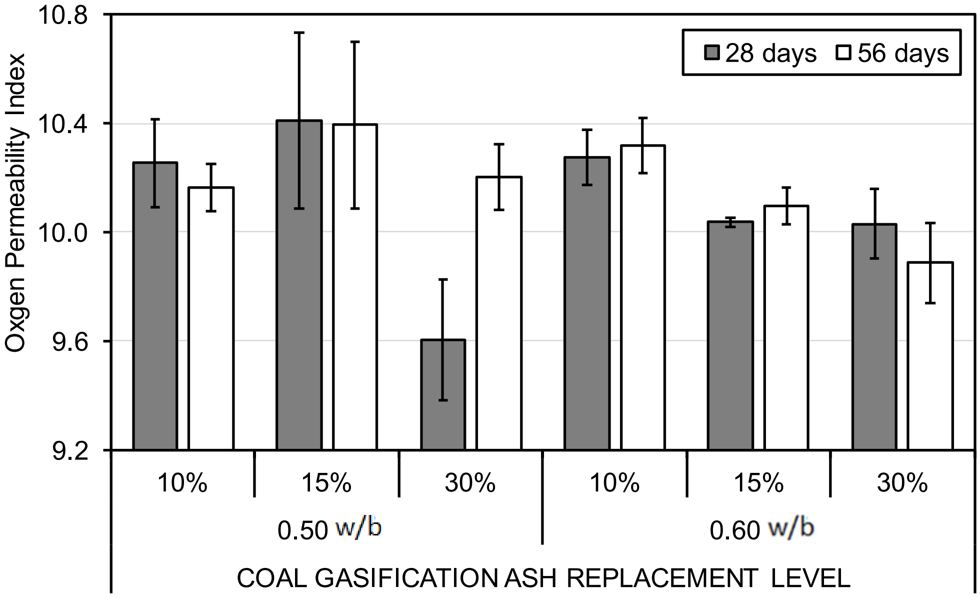

Figure 42: Influence of water-to-binder ratio on the oxygen permeability index results of CGA concrete

#### 4.5.1.2 Influence of binder type on oxygen permeability index

All the 0.50 w/b ratio concretes had good quality concrete. The 100% PC-0.50, 10% CGA-0.50, 15% CGA-0.50, 30% FA-0.50, and 30% CGA-0.50 concretes at 56-days of testing were also concrete of acceptable quality(see Figure 42). The same results were witnessed at 28 and 56-days of OPI testing conducted on the 100% PC-0.50 concretes. The 28 and 56-days OPI values of 10% CGA-0.50 and 15% CGA-0.50 concretes were greater than those observed for the 100% PC-0.50 concrete, while the OPI values of the 30% FA-0.50 and 100% PC-0.50 concretes were comparable.

#### 4.5.1.2.1 28-days testing age of OPI (w/b = 0.50)

The 28-days OPI value for the 10% FA-0.50 was less than that of the 100% PC-0.50 by a very small margin. The concrete with binder type 10% CGA with 0.50 w/b ratio had the highest influence on the OPI of concrete compared to those of 10% FA-0.50 and 10% WFA-0.50 concretes. The 15% FA-0.50 and 15% WFA-0.50 concretes had the same OPI values. The 15% CGA-0.50 concrete had the most influence on concrete, its observed OPI value was than 10% CGA-0.50, 30% CGA-0.50 and the other SCM-0.50 concretes. The 30% WFA-0.50 and 30% CGA-0.50 concretes had the same OPI values. Within the 30% replacement level for PC, FA-0.50 had the most influence on the OPI of concrete. There was no significant difference between the 100% PC-0.50 and 30% FA-0.50, 100% PC-0.50 and 10% CGA-0.50, and lastly 100% PC-0.50 and 15% CGA-0.50 concretes. For the secondary control, there was no significant difference between the 10% FA-0.50 and 10% WFA-0.50, as well as 15% FA-0.50 and 15% WFA-0.50 concretes. Appendix D presents the additional OPI and statistical information.

#### 4.5.1.2.2 56-days testing age of OPI (w/b = 0.50)

The 10% FA-0.50 concrete had the same OPI value as that of 100% PC-0.50 concrete. The 10% CGA with 0.50 w/b ratio had more influence on the OPI of concrete than 10% FA and 10% WFA with 0.50 w/b ratio. The 15% CGA-0.50 concrete had the highest OPI values, within the 15% replacement level of PC and among the SCMs-0.50 concretes. The 30% CGA-0.50 concrete had higher OPI values than those of the 30% FA-0.50 and 30% WFA-0.50 concretes. There was no significant difference between the 100% PC-0.50 and 10% FA-0.50, 100% PC-0.50 and 10% WFA-0.50, 100% PC-0.50 and 10% CGA-0.50, 100% PC-0.50 and 15% WFA-0.50, 100% PC-0.50 and 15% CGA-0.50, 100% PC-0.50 and 30% FA-0.50, together with 100% PC-0.50 and 30% CGA-0.50 concretes for the primary control. There was no significant difference between the 10% FA-0.50 and 10% WFA-0.50, 10% FA-0.50 and 10% CGA-0.50, 15% FA-0.50 and 15% WFA-0.50, as well as 30% FA-0.50 and 30% CGA-0.50.

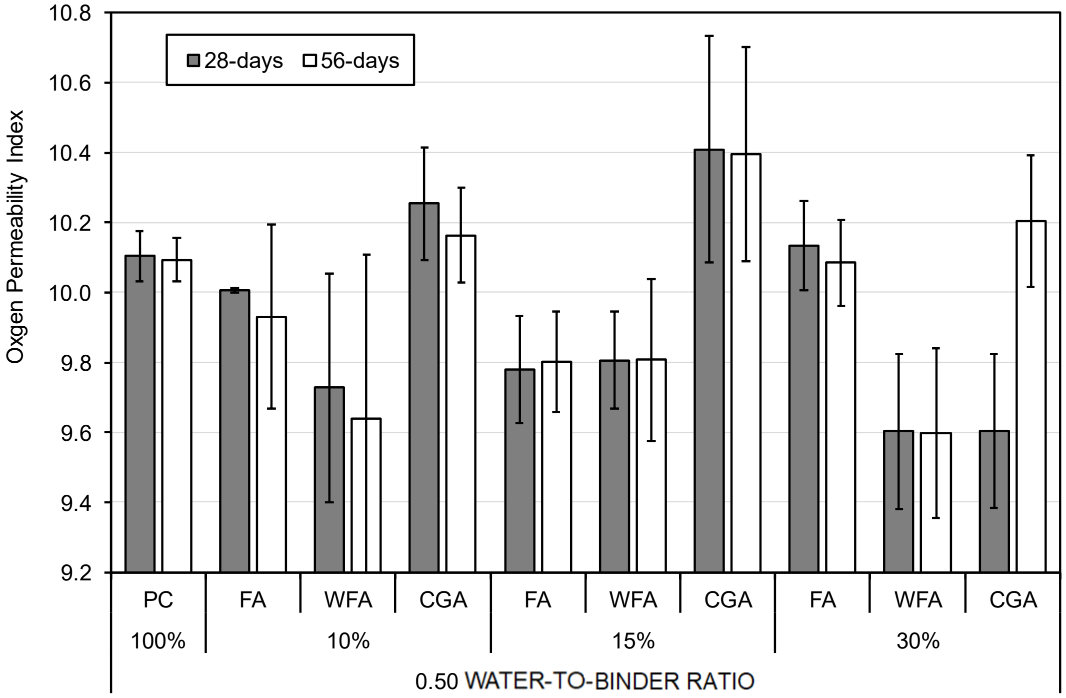

Figure 43: Influence of binder type on the oxygen permeability index results with 0.50 water-to-binder ratio

All the 0.60 w/b ratio concretes had good quality concrete. 100% PC-0.60, 10% CGA-0.60, 15% CGA-0.60, 30% FA-0.60 and only 30% WFA had excellent quality concrete, Figure 44. The 100% PC-0.60 concrete at 28-days of test had a similar OPI value to the 100% PC-0.60 concrete at 56-days of testing. The OPI value of the 10% CGA-0.60 concrete, at 28-days was slightly higher than that observed for the 100% PC-0.60 concrete. The 30% WFA-0.60 concrete had comparable OPI values to the 100% PC-0.60 concrete at 56-days of testing.

#### 4.5.1.2.3 28-days testing age of OPI (w/b = 0.60)

The 30% FA-0.60 concrete OPI results were less than that of the 100% PC-0.60 by 1%, their the OPI values were indicative of excellent quality concrete (>10). The 10% CGA-0.60 concrete had the highest influence on the OPI of concrete when considering all the SCM-0.60 concretes. The 10% FA-0.60 and 10% WFA-0.60 concretes had similar OPI values, while the 15% FA-0.60 and 15% WFA-0.60 concretes had the same OPI values. The 15% CGA-0.60 concrete had the most influence on the OPI of concrete compared to the 15% FA-0.60 and 15% WFA-0.60 concretes. The OPI values of the 30% FA-0.60 and 30% CGA-0.60 concretes were similar. The 30% WFA-0.60 concrete had the highest OPI values compared to the 30% FA-0.60 and 30% CGA-0.60 concretes. There was no significant difference between the 100% PC-0.60 and 15% WFA-0.60, 100% PC-0.60 and 15% CGA-0.60, 100% PC-0.60 and 30% FA-0.60 and lastly 100% PC-0.60 and 30% CGA-0.60 concretes. There was no significant difference between the 10% FA-0.60 and 10% WFA-0.60, 15% FA-0.60 and 15% WFA-0.60, as well as 30% FA-0.60 and 30% CGA-0.60 concretes. Appendix D presents the additional OPI and statistical information.

#### 4.5.1.2.4 56-days testing age of OPI (w/b = 0.60)

At 56 days, the same OPI value was obtained for the 30% WFA-0.60and 100% PC-0.60 concretes. The 10% CGA-0.60 had most influence on the OPI of concrete when considering all the SCm-0.60 concretes. The 15% WFA-0.60 and 15% CGA-0.60 concretes had a similar influence on the OPI of concrete. The 30% WFA-0.60 concrete had more influence on the concrete OPI compared to the 30% FA-0.60 and 30% WFA-0.60 concrete. There was no significant difference between the 100% PC-0.60 and 10% CGA-0.60, 100% PC-0.60 and 15% WFA-0.60, 100% PC-0.60 and 15% CGA-0.60, together with 100% PC-0.60 and 30% WFA-0.60 concretes. There was no significant difference between the 10% FA-0.60 and 10% WFA-0.60, 15% FA-0.60 and 15% WFA-0.60, 15% FA-0.60 and 15% CGA-0.60, as well as 30% FA-0.60 and 30% CGA-0.60 concretes.

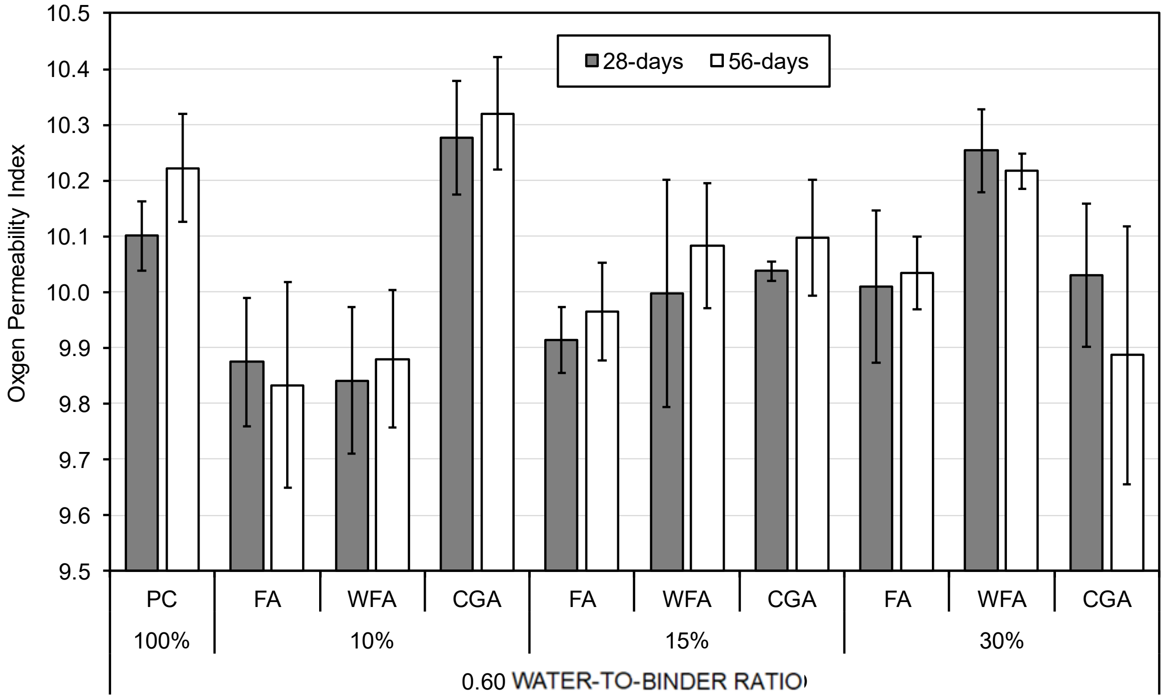

Figure 44: Influence of binder type on the oxygen permeability index results with 0.60 water-to-binder ratio

### 4.5.1.3 Influence of replacement level on oxygen permeability index

The quality of the WFA-0.50 and CGA-0.50 concrete was slightly better with the 15% replacement level for PC while the quality of 30% CGA-0.50 concrete improved with age. The

OPI values of the FA-0.50 concrete at 15% replacement level for PC were lower than those with the 10% and 30% replacement level for PC, considering the 28 and 56-days of testing ages (Figure 45). The 30% FA replacement level for PC had the most influence on OPI of concrete, compared to the 10% and 15% FA replacement levels for PC. Mehta (2004) reported that FA at 25-35% replacement level for PC improves the durability of concrete. The SCM fines occupy the voids, reducing permeability, increasing the concretes packing density thereby improving durability of concrete (Devi, 2018; Grieve, 1991; Zode, 1999; Lamond, 2006). Higher OPI values were witnessed for 30% FA out of the FA-0.50 concretes, 15% WFA out of the WFA-0.50 concretes and 15% CGA out of the CGA concretes.

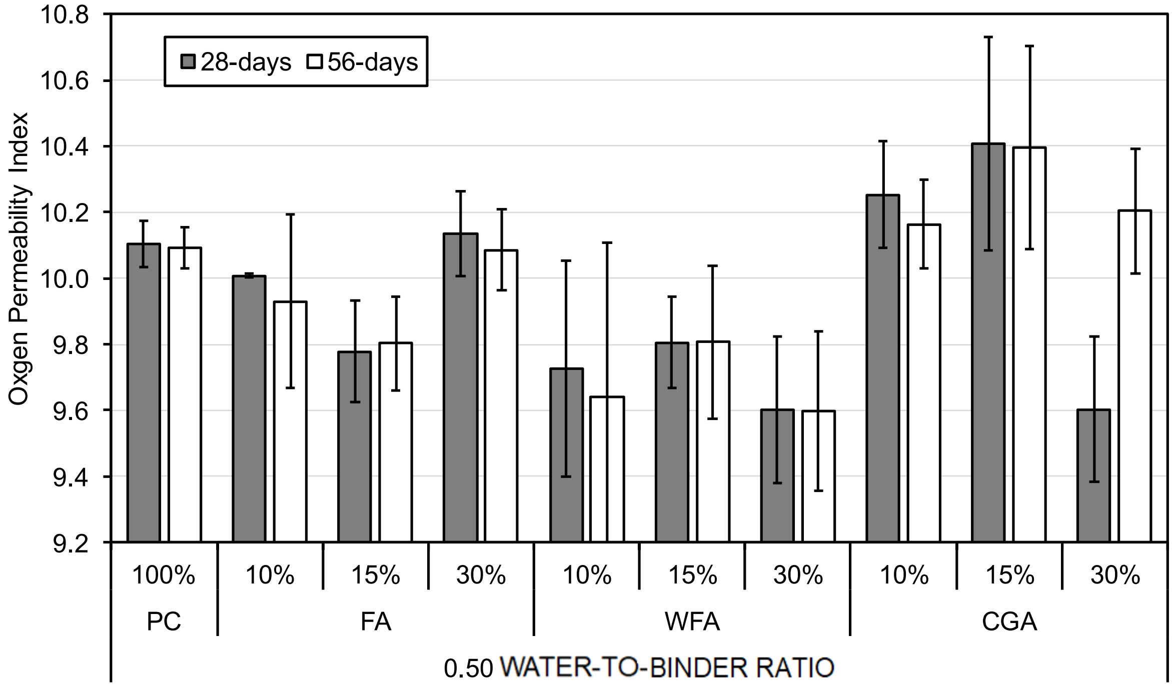

Figure 45: Influence of replacement level on the oxygen permeability index results with 0.50 water-to-binder ratio

There was a similarity in the OPI results of the FA-0.60 and WFA-0.60 concrete. The quality of the FA-0.60 and WFA-0.60 concretes improved with increasing replacement for PC at both the 28 and 56-day test ages (Figure 46). Supplementary cementitious material are finer than PC, the higher their replacement level for PC the higher the density, and a barrier is formed due to the SCMs occupying the voids which results in improved durability (Ballim, et al., 2009; Grieve, 1991). The OPI values of the 10% CGA-0.60 concretes were similar to those of the 30% WFA-0.60 concrete. There was no substantial improvement in the OPI values of the SCM-0.60 concretes with age. The OPI of the concrete was influenced most by 30% FA from the FA-0.60 concretes, 30% WFA from the WFA-0.60 concretes and 10% CGA from the CGA-0.60.

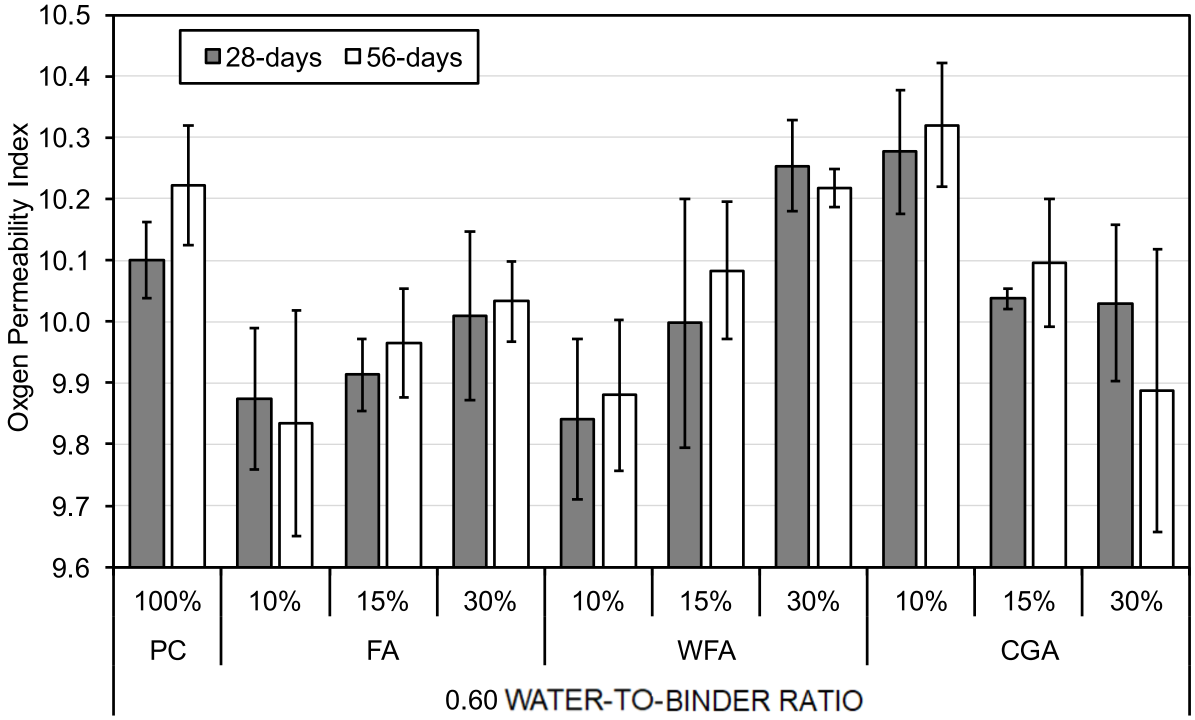

Figure 46: Influence of replacement level on the oxygen permeability index results with 0.60 water-to-binder ratio

### 4.5.2 Water Sorptivity Index results

The water sorptivity index (WSI) test involved the uni-directional absorption of water into one face of a pre-conditioned concrete disc specimen. At predetermined time intervals, the sample was weighed to determine the mass of water absorbed, and the water sorptivity was determined from the plot of the mass of water absorbed versus square root of time. Low water sorptivity index values indicate a low rate of water absorption (high durability), and a high index values indicate a more permeable concrete with a high rate of water absorption (low durability). According to the durability index test assessment criterion, WSI values which range between 6 to 10 mm/hr$^{0.5}$ are considered to be indicative of good quality concrete (Alexander, et al., 2001; Mukadam, 2014).

#### 4.5.2.1 Influence of w/b ratio on water sorptivity index

Most of the WSI values witnessed were indicative of poor-quality concrete (>10 mm/hr$^{0.5}$). Lower WSI values from concretes with the 0.50 w/b ratio were witnessed at 28 and 56-days of testing but most of their WSI values were too high and indicating poor quality concrete. Only FA concretes had reducing WSI values with age, implying an improvement in the durability of concrete. The 100% PC-0.50 concrete had lower WSI values than 100% PC-0.60 at 28-days and 56-days of testing (Figure 47). The WSI values of the 100% PC-0.50 and 100% PC-0.60 concretes were between 10 and 15 mm/hr$^{0.5}$ indicating poor quality concretes.

It was expected that the blends with 0.50 w/b ratio would yield lower WSI values compared to those with the 0.60 w/b ratio due to an increase in concrete porosity which is influenced by an increase in capillary porosity within the concrete matrix when using higher w/b ratios (Ballim, et al., 2009; Alexander, 1998). The lower WSI values indicated less permeability, which translates to better quality concrete since the concrete has less voids, reduced bleeding and increased density (Lamond, 2006). In this study, it was observed that the WSI values increased as the w/b ratio increased from 0.50 to 0.60. Hence, an increase in the w/b ratio results in an increase moisture penetrability into the concrete. In the 28-days WSI tests, it was observed that the quality of FA concrete did not improve as the w/b ratio increased, a similar outcome was observed at 56-days of testing (Figure 48). The WSI values of FA-0.50 and FA-0.60 concretes did not improve with age.

All the WSI values of the FA-0.50 concretes at 28-days of testing indicated poor quality concrete but at 56-days of testing, 10% FA-0.50 and 30% FA-0.50 had WSI values indicating good quality concrete. All the FA-0.60 concretes were of poor quality at 28-days of testing. At 56-days of testing, only 30% FA-0.60 concrete was considered to be of good quality. At 28 and 56-days of testing, poor to very poor WSI concrete values were observed for all WFA blends for both w/b ratios, see Figure 49. The WFA-0.50 concretes had lower WSI values at 56-days of testing, suggesting an improvement in the concrete quality. For the 0.60 w/b ratio, only the 10% WFA and 30% WFA concrete improved with age. A similar observation was made for the CGA concretes, see Figure 50. At 28 and 56-days of testing, poor to very poor CGA concrete results were observed for the CGA concretes for both w/b ratios. The WSI values of the CGA-0.60 concretes reduced with ages. For 0.50 w/b ratio, only 10% CGA and 30% CGA improved with age. Further investigations into the micro-structure of WFA and CGA are required. .

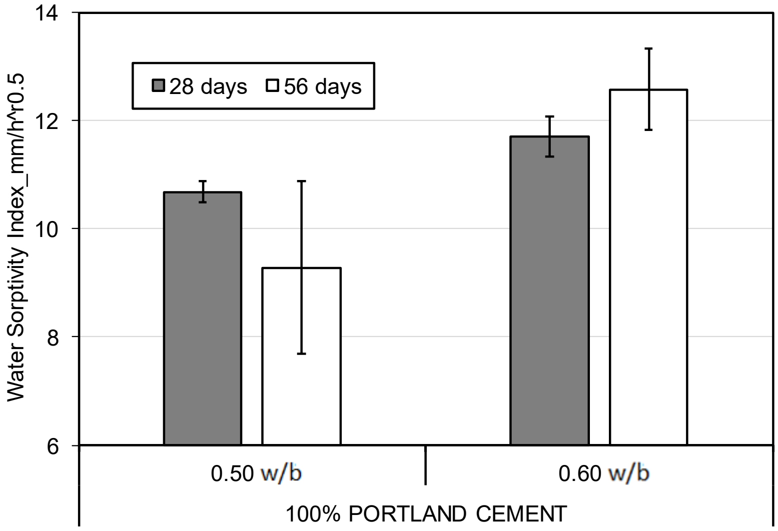

Figure 47: Influence of the water-to-binder ratio on the water sorptivity index results of 100% PC concrete

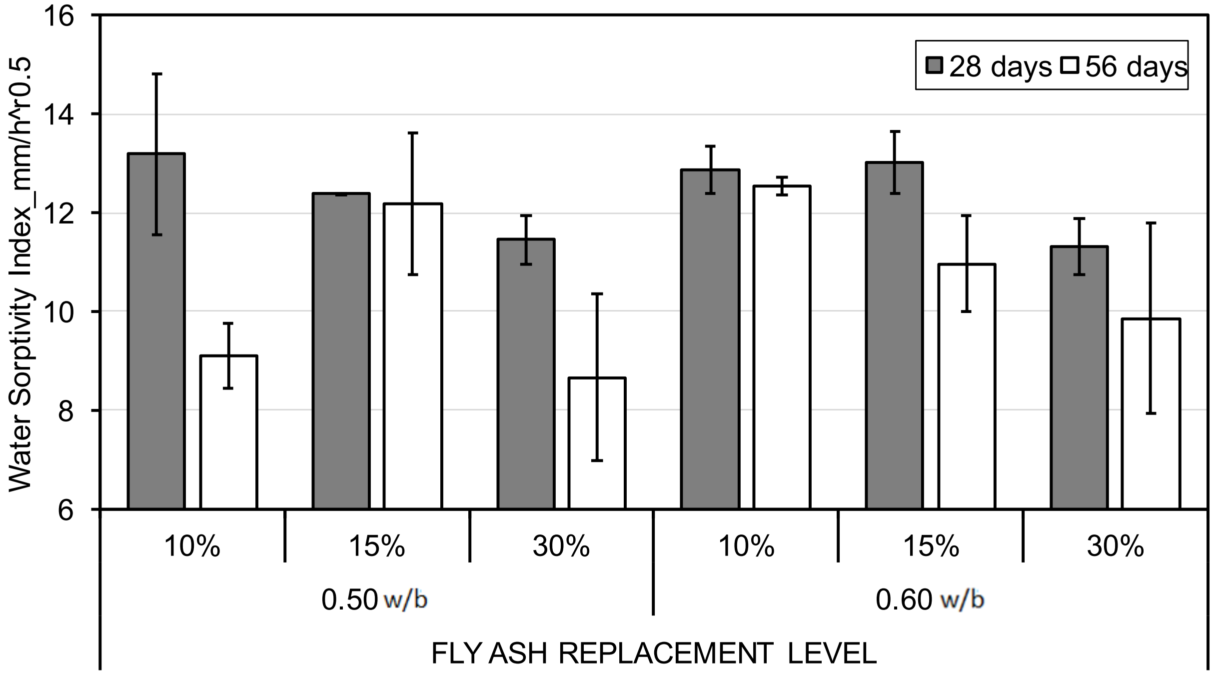

Figure 48: Influence of the water-to-binder ratio on the water sorptivity index results of FA concrete

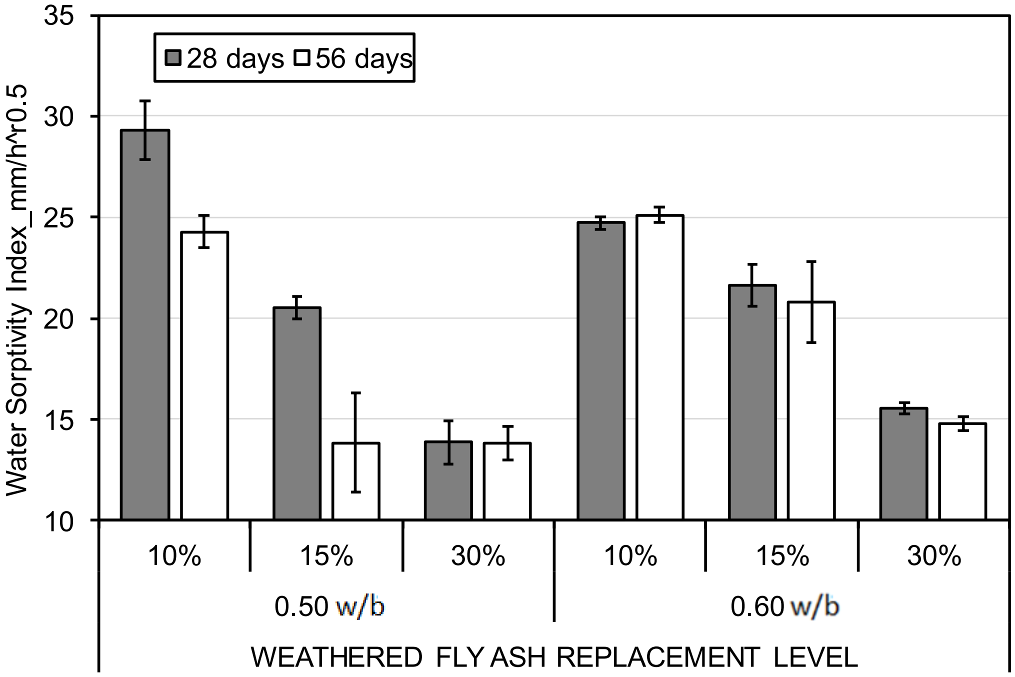

Figure 49: Influence of the water-to-binder ratio on the water sorptivity index results of WFA concrete

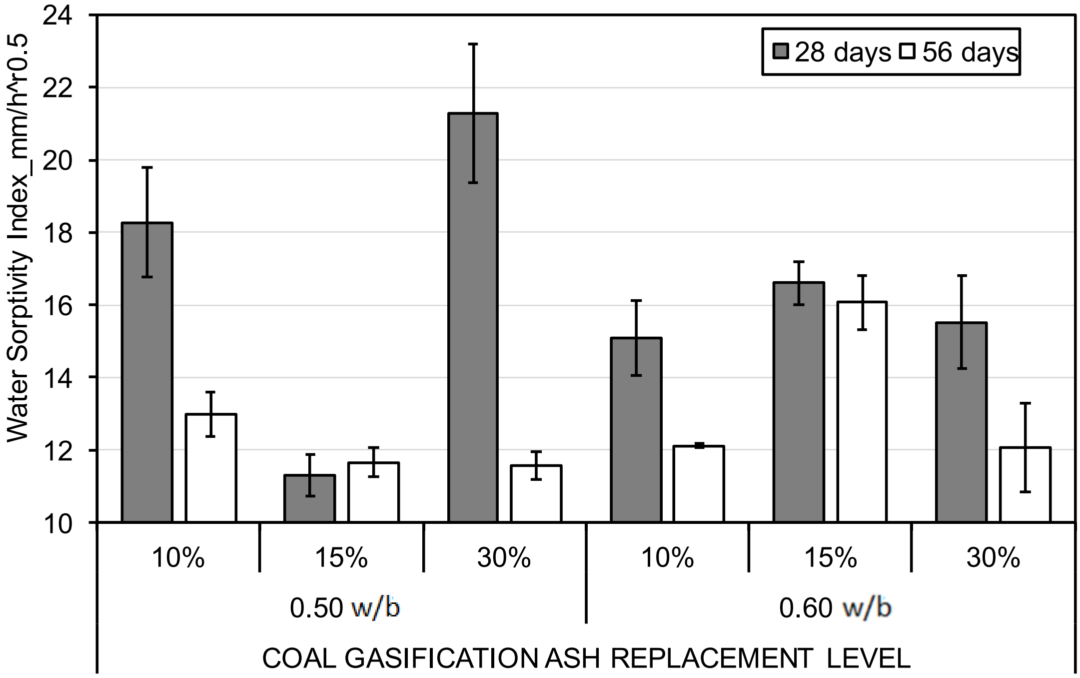

Figure 50: Influence of the water-to-binder ratio on the water sorptivity index results of CGA concrete

#### 4.5.2.2 Influence of binder type on water sorptivity index

Only the 30% FA-0.50 concrete had better quality than 100% PC-0.50 concrete at 56-days of testing, see Figure 51. The 10% FA-0.50 and 100% PC-0.50 concretes had the same WSI values at 56-days of testing. At 28-days of testing, none of the SCM concretes had lower WSI values than that of 100% PC-0.50 concrete. The WSI values of the 10% WFA-0.50 and 10% CGA-0.50 concretes were higher than those of the 10% FA-0.50 concretes. The WSI values of the 30% WFA-0.50 and 30% CGA-0.50 concretes were higher than those of the 30% FA-0.50 concretes. The 15% CGA-0.50 concrete had the highest influence on the water sorptivity index of concrete compared to the 15% FA-0.50 and 15% WFA-0.50 concretes.

#### 4.5.2.2.1 28-days testing age of WSI (w/b = 0.50)

All the WSI values of the SCM-0.50 concretes were greater than that of the 100% PC-0.50 concretes. The FA-0.50, WFA-0.50 and CGA-0.50 concretes did not have a positive influence on the WSI of concrete. Mehta (2004) reported that FA at 25-35% had a positive impact on the durability of concrete. The fines occupy the voids, reducing permeability, increasing the density and improving durability of concrete (Devi, 2018; Grieve, 1991; Zode, 1999; Lamond, 2006). The WSI values in Figure 51 indicate that the SCM-0.50 concretes are highly permeable and resulted in high water absorptive rates. There was no significant difference between the 100% PC-0.50 and 15% CGA-0.50, as well as 100% PC-0.50 and 30% FA-0.50 concretes. There was a significant difference between FA-0.50 and WFA-0.50, as well as FA-0.50 and FA-0.50 concretes. The statistical details are presented in Appendix E. The FA-0.50 concretes had better WSI values than those observed for the WFA-0.50 and CGA-0.50 concretes. The difference in particle sizes (FA was 45μm and Sasol ashes were 70 μm) may have been one of the contributing factors to the difference in WSI values, more voids were occupied by FA than WFA and CGA, making the FA-0.50 concrete denser and more impermeable. The internal structure of WFA and CGA concretes requires further investigation.

#### 4.5.2.2.2 56-days testing age of WSI (w/b = 0.50)

Only the 10% FA-0.50 and 30% FA-0.50 concretes had WSI values below that observed for 100% PC-0.50 concretes. There was a 0.2 $mm/hr^{0.5}$ difference between the WSI values of the 100% PC-0.50 and 10% FA-0.50 concretes, suggesting that the 10% FA-0.50 concrete does not have much of an influence on the WSI of concrete. The 15% FA-0.50 concrete did not have a positive influence on the WSI of concrete. The observation made regarding FA satisfied the findings by Mehta (2004) that FA at 25-35% had a positive impact on the durability of concrete. At 56-days of testing the quality of most of the concretes improved, the WSI values were lower than those observed at 28-days of testing. Figure 51 indicates that there is a general reduction in WSI values with age, which means should the WSI values be measured beyond 56-days a reduction in the rate of water absorption would be witnessed. One of the most important things to note would be the age at which WSI values are low enough to be considered as indicating good quality concrete. The FA-0.50 concretes had the lowest WSI values at 10%, 15% and 30% replacement level for PC (28 and 56-days of testing). The noted difference in shape and size of the FA particles to those of WFA and CGA may be contributing to the differences in WSI values. There was no significant difference between the 100% PC-0.50 and 10% FA-0.50, 100% PC-0.50 and 15% WFA-0.50, as well as 100% PC-0.50 and 30% FA-0.50 concretes. There was no significant difference between the 15% FA-0.50 and 15% WFA-0.50, together with 15% FA-0.50 and 15% CGA-0.50 concretes.

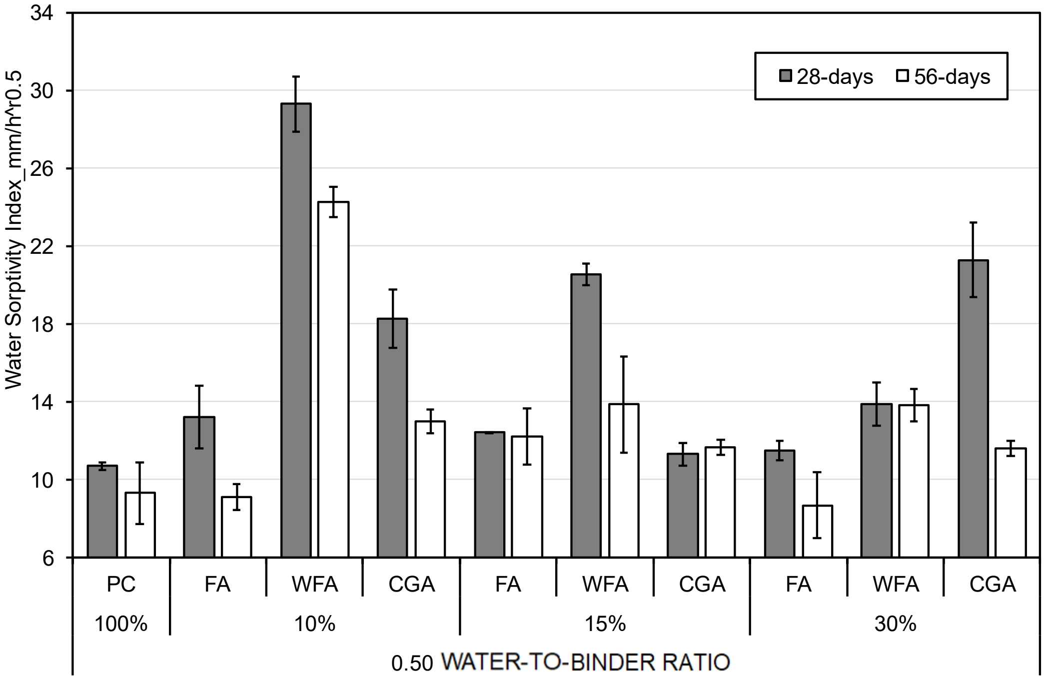

Figure 51: Influence of binder type on the water sorptivity index results with 0.50 water-to-binder ratio

Only the 30% FA-0.60 provided better quality concrete than 100% PC-0.60, at 28 and 56-days of testing, see Figure 52. The quality of the 30% FA-0.60 concrete was considered as poor at 28-days and good at 56-days due to a 1.4 mm/hr$^{0.5}$ decrease. At 28-days of testing, the WFA-0.60 and CGA-0.60 concretes had their WSI values indicating very poor-quality concrete (> 15 mm/hr$^{0.5}$). Even though the 0.60 w/b ratio concrete becomes more permeable than that of 0.50 w/b, the observed WSI for the WFA-0.60 and CGA-0.60 are unrealistic. A combination of the effect of the 0.60 w/b ratio, particle size, particle shape and internal and micro-cracks may be impacting the WSI values.

### 4.5.2.2.3 28-days testing age of WSI (w/b = 0.60)

All the WSI values of the WFA-0.60 and CGA-0.60 concretes were greater than that of the 100% PC-0.60 concrete (Figure 52). The 30% FA-0.60 concretes at 28 and 56-days of testing had the most positive influence on the WSI of concrete, in accordance to literature (Mehta, 2004). There was no significant difference between 100% PC-0.60 and 30% FA-0.60. There was a significant difference between the FA-0.60 and WFA-0.60, as well as FA-0.60 and CGA-0.60 concretes. The statistical details are presented in Appendix E. The 10% FA, 15% FA and 30% FA concretes with 0.60 w/b ratio had the lowest WSI values when compared to WFA, and CGA at 10%, 15% and 30% replacement level for PC with a 0.60 w/b ratio.

#### 4.5.2.2.4 56-days testing age of WSI (w/b = 0.60)

The WSI values of the 10% CGA-0.60, 15% FA-0.60, 30% FA-0.60 and 30% CGA-0.60 concretes were lower than that observed for the 100% PC-0.60 concrete (Figure 52). The WSI values of the 100% PC-0.60 and 10% FA-0.60 concrete was the same, implying that the 10% FA-0.60 does not have the influence of reducing the penetrability of concrete to water. The 15% FA-0.60 and 30% FA-0.60 concretes had reduction rates of water absorption. At 56-days of testing the quality of most of the concretes improved, the observed WSI values were lower than those observed at 28-days of testing. There was no significant difference between the 100% PC-0.60 and 10% FA-0.60, 100% PC-0.60 and 10% CGA-0.60, 100% PC-0.60 and 15% FA-0.60, 100% PC-0.60 and 30% CGA-0.60, as well as 30% FA-0.60 and 30% CGA-0.60.

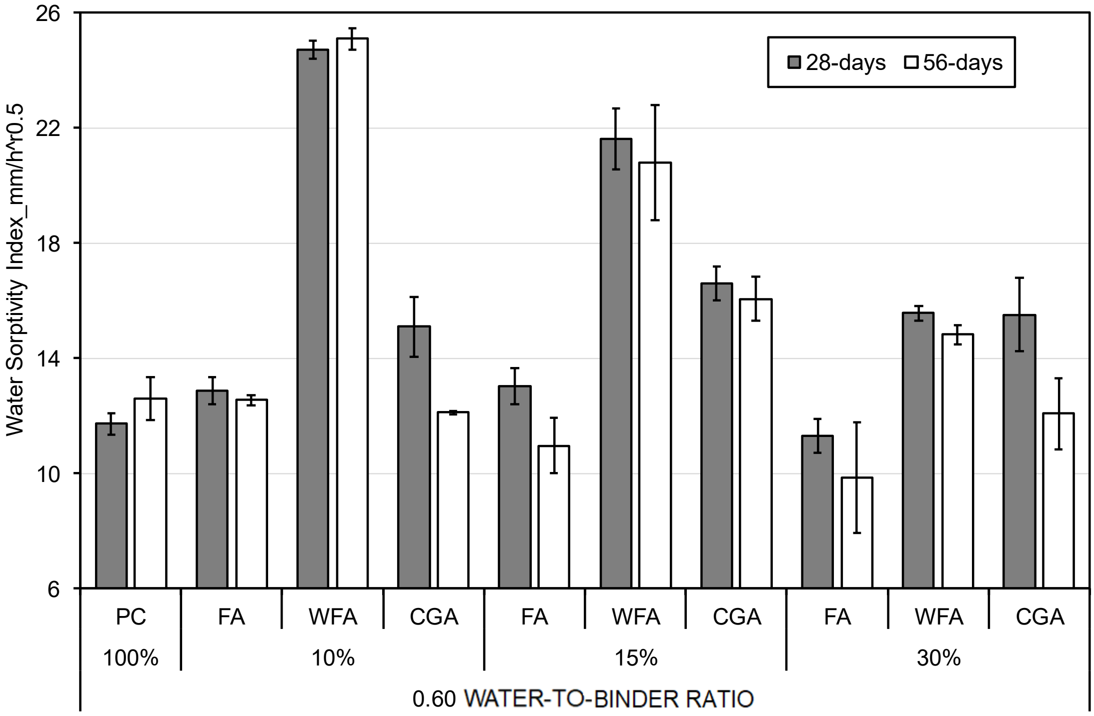

Figure 52: Influence of binder type on the water sorptivity index results with 0.60 water-to-binder ratio

### 4.5.2.3 Influence of replacement level on water sorptivity index

All WSI values of the FA-0.50, WFA-0.50 and CGA-0.50 concretes for all replacement levels for PC were higher than those observed for 100% PC-0.50 concrete at 28-days of testing (Figure 53). The FA-0.50 concretes had lower WSI values than the CGA-0.50 and WFA-0.50 concretes. At 28-days of testing, the 30% replacement level for PC by FA with a 0.50 w/b had the lowest WSI value, but they indicated poor quality concrete (Alexander, et al., 1999). At 56-days of testing, the 30% replacement level for PC by FA with 0.50 had the lowest WSI value, but the quality of concrete was considered good (Alexander, et al., 1999). The WSI values of the SCM-0.50 concretes at 28-days of testing indicated that the replacement levels for PC by FA-0.50, WFA-0.5, and CGA-0.50 did not reduce the rate of water absorption. The 15% CGA-0.50 concrete at 28-days of testing had the lowest WSI value compared to the 10% CGA-0.50 and 30% CGA-0.50 concretes. The 15% CGA-0.50 and 30% CGA-0.50 concretes had the same WSI value at 56-days of testing, and it was lower than that observed for the 10% CGA-0.50 concrete. It was observed that WSI value of the WFA-0.50 concretes decreased with increasing replacement level for PC. The WSI values for 10% and 15% WFA concrete with 0.50 w/b reduced further with age. However, the WSI value of the 30% WFA-0.50 concrete did not improve with age. The observation of the WSI values of the 30% WFA-0.50 concrete may be interpreted as follows; the WSI values will continue to reduce with increasing replacement level for PC by WFA and the development with age may go unnoticed or be similar to that of the 10% WFA-0.50 and 15% WFA-0.50 concretes (Figure 53).

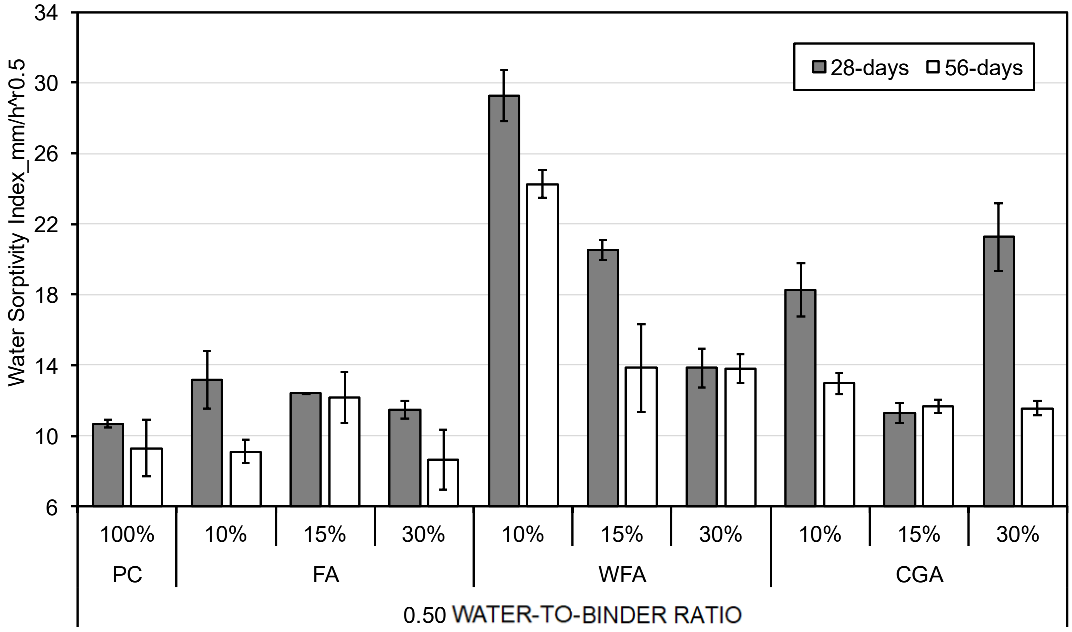

Figure 53: Influence of replacement level on the water sorptivity index results with 0.50 water-to-binder ratio

All the WSI values of the WFA-0.60 and CGA-0.60 concretes for all replacement levels for PC were greater than those observed for the 100% PC-0.60 concrete at 28-days of testing (Figure 54). The 15% FA-0.60 and 30% FA-0.60 concretes had lower WSI values than the 15% and 30% of CGA-0.60 and WFA-0.60 concretes. The 30% replacement level for PC by FA-0.60 had the most influence on the WSI of concrete, at 28-days and 56-days of testing the WSI values were lower than those of the 100% PC-0.60 concrete. The 10% CGA-0.60 and 10% FA-0.60 concretes had related WSI values at 56-days of testing. The WSI values of the WFA-0.60 concrete reduced with increasing replacement levels for PC, indicating an increase in the density and a reduction in permeability, meaning an overall improvement in the durability of concrete. The WFA-0.60 concretes like the WFA-0.50 concretes have WSI values decreasing with increasing replacement levels for PC, but unlike the 30% WFA-0.50 concrete, the WSI values of the 30% WFA-0.60 concrete reduced with age. It seems that a replacement level for PC higher than 30% may lead to further reduction of the WSI values.

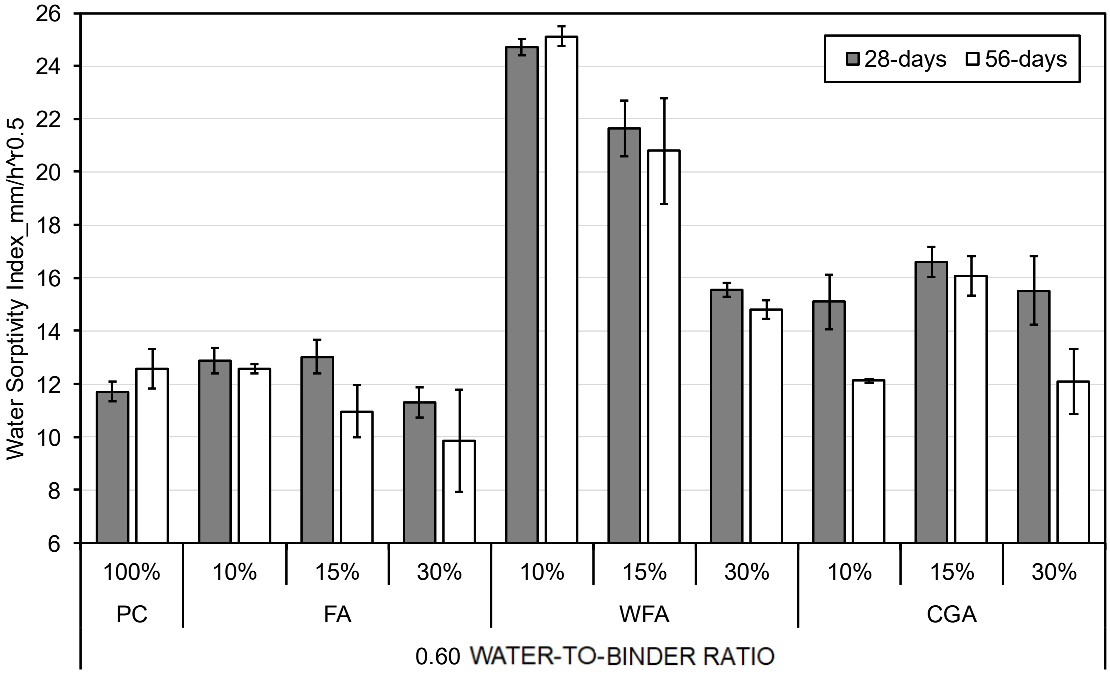

Figure 54: Influence of replacement level on the water sorptivity index results with 0.60 water-to-binder ratio

### 4.5.3 Chloride Conductivity

Streicher (1997) developed a rapid chloride conductivity test in which virtually all ionic flux occurs by conduction after a 10 V potential difference is applied across the samples two faces. A low chloride conductivity index is an indication that the concrete has the ability to resist chloride ingress, therefore the concrete is less permeable, has less voids, reduced bleeding when it was cast and has few interconnected pores (Lamond, 2006). Chloride conductivity index values between 0.75 and 1.5 mS/cm indicate good quality concrete, while values below 0.75 mS/cm indicate excellent quality concrete and those above 1.5 mS/cm indicate poor quality concrete.

#### 4.5.3.1 Influence of w/b ratio on chloride conductivity index

The FA-0.50 and WFA-0.50 concretes had the lowest CCI values at 28 and 56-days of testing age. The concretes which had the lowest CCI values were those with a 0.50 w/b ratio. The CCI values of the 100% PC-0.50 concrete at 28 and 56-days of testing indicate that the concrete was of good quality with a conductivity of less than 0.75 mS/cm (Figure 55) The 100% PC-0.60 concrete had CCI values indicating good quality. The CCI values of the 100% PC-0.50 and 100% PC-0.60 reduced with age, showing an improvement in the concrete quality with age.

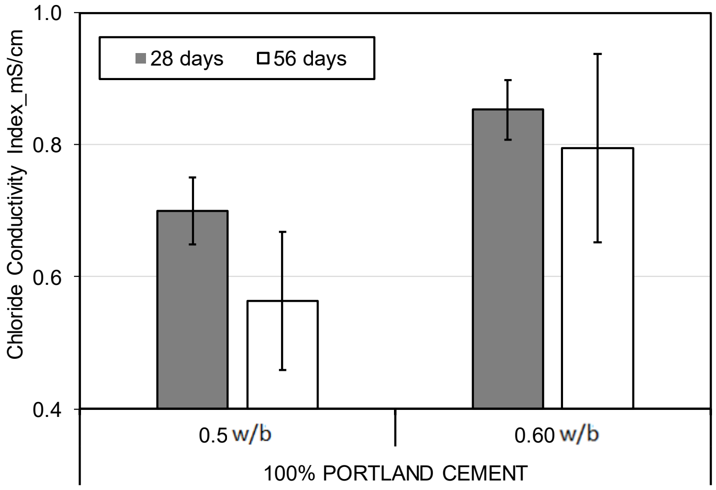

Figure 55: Influence of water-to-binder ratio on the chloride conductivity index results of 100% PC concrete

The CCI values of the FA-0.50 concretes are lower than those of the FA-0.60 concretes (see Figure 56). The increase in the w/b ratio increases the permeability of the concrete and reduces chloride ingress resistance, resulting in higher CCI values, this was shown in literature (Devi, 2018; Kosmatka, et al., 2002; Zulu, 2017). The CCI values of the WFA-0.50 concretes were lower than those of the WFA-0.60 concretes, see Figure 57. The 0.50 w/b ratio in WFA concrete had more influence on the CCI of concrete than the 0.60 w/b ratio. Most of the CCI values for the WFA-0.50 and WFA-0.60 concretes indicate excellent quality concrete at both testing ages. The CCI values of the 15% CGA-0.50 and 30% CGA-0.50 concretes were lower than those of the 15% CGA-0.60 and 30% CGA-0.60 concretes, see Figure 58. The 0.50 w/b ratio of the CGA concretes had more influence on the CCI of concrete than the 0.60 w/b ratio. However, the 10% CGA-0.60 concrete was of better quality than the 10% CGA-0.50 concrete.

The 10% CGA-0.50 concrete at 28 and 56-days testing age had the same CCI value, implying that the quality of concrete did not improve with age. The 10% CGA-0.50, 10% CGA-0.60 and 30% CGA-0.50 concretes had CCI values less than 0.75 mS/cm implying that they were all of excellent quality concrete.

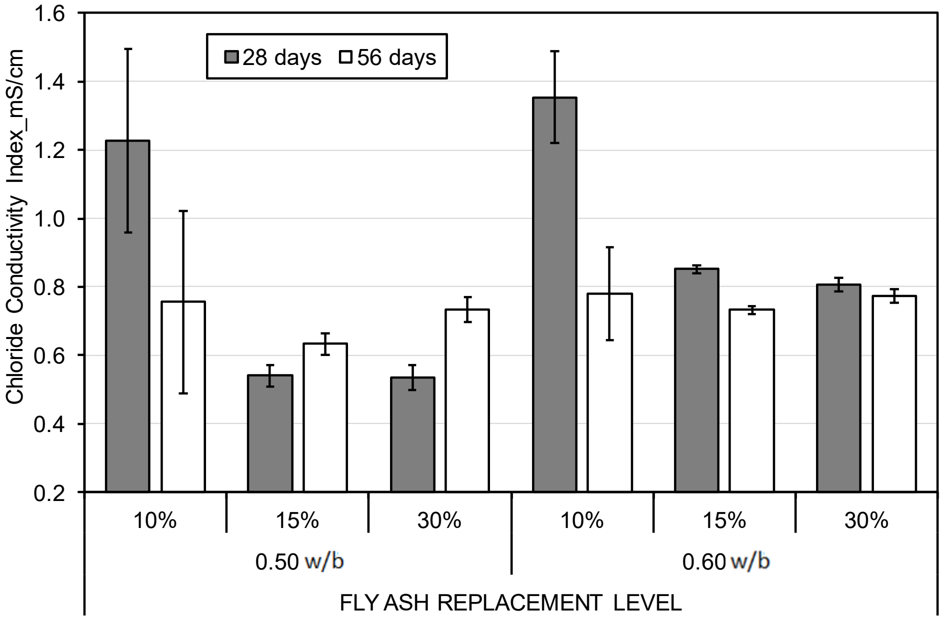

Figure 56: Influence of water-to-binder ratio on the chloride conductivity index results of FA concrete

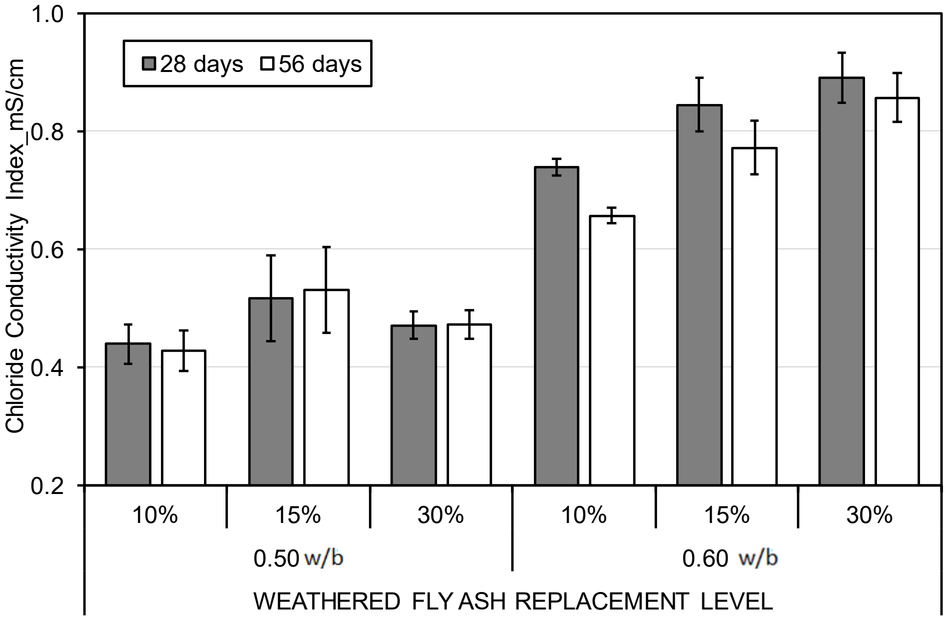

Figure 57: Influence of water-to-binder ratio on the chloride conductivity index results of WFA concrete

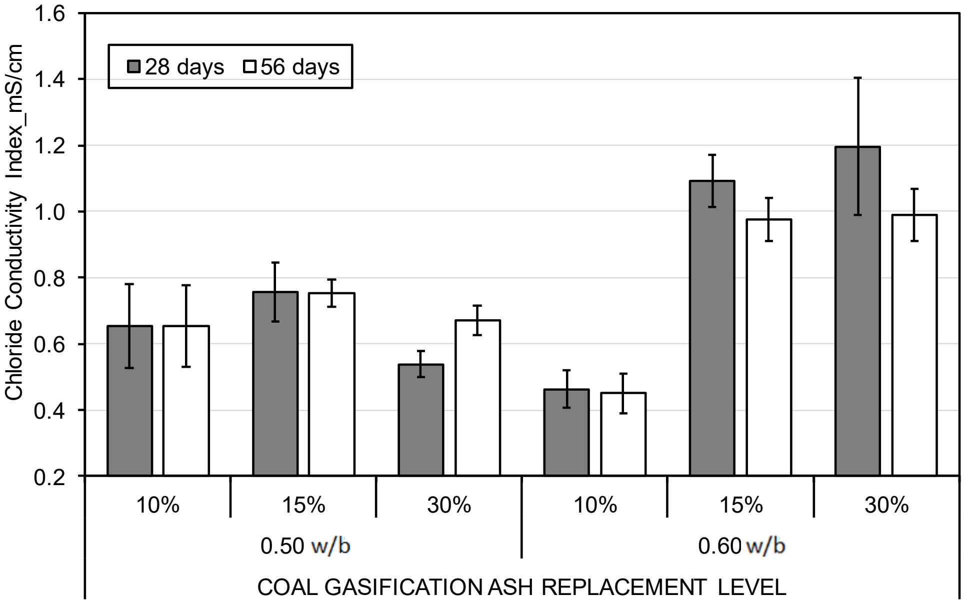

Figure 58: Influence of water-to-binder ratio on the chloride conductivity index results of CGA concrete

#### 4.5.3.2 Influence of binder type on chloride conductivity index

Most of the SCM-0.50 concretes had lower CCI values when compared to the 28-days test of the 100% PC-0.50 concrete. Figure 59 presents the results being discussed in this section. Only the 10% FA-0.50 and 15% CGA-0.50 concretes had CCI values greater than that of the 100% PC-0.50 concrete. At 56-days of testing, only the 10% WFA-0.50, 15% WFA-0.50 and 30% WFA-0.50 concretes had CCI values that were less than that of the 100% PC-0.50 concrete.

##### 4.5.3.2.1 28-days testing age of CCI (w/b = 0.50)

The CCI values of the 10% WFA-0.50, 10% CGA-0.50, 15% FA-0.50, 15% WFA-0.50, 30% FA-0.50, 30% WFA-0.50 and 30% CGA-0.50 concretes were less than that of the 100% PC-0.50 concrete. The 10% FA-0.50 and 15% CGA-0.50 concrete at 28-days did not have a positive influence on the CCI of concrete, their CCI values were higher than that of 100% PC-0.50 meaning that they did not improve the resistance of concrete to chloride ingress. There was no significant difference in the CCI results of the 100% PC-0.50 and 10% CGA-0.50 concrete, and the 100% PC-0.50 and 15% CGA-0.50 concrete. There was a significant difference between 10% FA-0.50 and 10% WFA-0.50, 10% FA-0.50 and 10% CGA-0.50, 15% FA-0.50 and 15% CGA-0.50, as well as 30% FA-0.50 and 30% WFA-0.50. The significant difference between the 10% FA-0.50 and 10% WFA-0.50, as well as 10% FA-0.50 and 10% CGA-0.50 concretes was due to the 10% WFA-0.50 and 10% CGA-0.50 concretes having lower CCI values than 10% FA-0.50. The 10% WFA-0.50 and 10% CGA-0.50 had the most positive influence on the CCI of concrete. The statistical details are presented in Appendix F.

The WFA-0.50 concretes had lower CCI values than those of the FA-0.50 concretes. This implies that the WFA-0.50 concretes provided better resistance to chloride ingress than the FA-0.50 concretes .

### 4.5.3.2.2 56-days testing age of CCI (w/b = 0.50)

The 10% WFA-0.50, 15% WFA-0.50 and 30% WFA concretes had lower CCI values compared to the 100% PC-0.50 concretes. The WFA-0.50 concretes had a more positive influence on the CCI of concrete than the FA-0.50 concretes. There was no significant difference between the CCI values of the 100% PC-0.50 and 10% FA-0.50, 100% PC-0.50 and 10% WFA-0.50, 100% PC-0.50 and 10% CGA-0.50, 100% PC-0.50 and 15% FA-0.50, 100% PC-0.50 and 15% WFA-0.50, 100% PC-0.50 and 30% WFA-0.50, and 100% PC-0.50 and 30% CGA-0.50 concretes. There was a significant difference between the 10% FA-0.50 and 10% WFA-0.50, and the 30% FA-0.50 and 30% WFA-0.50 concretes.

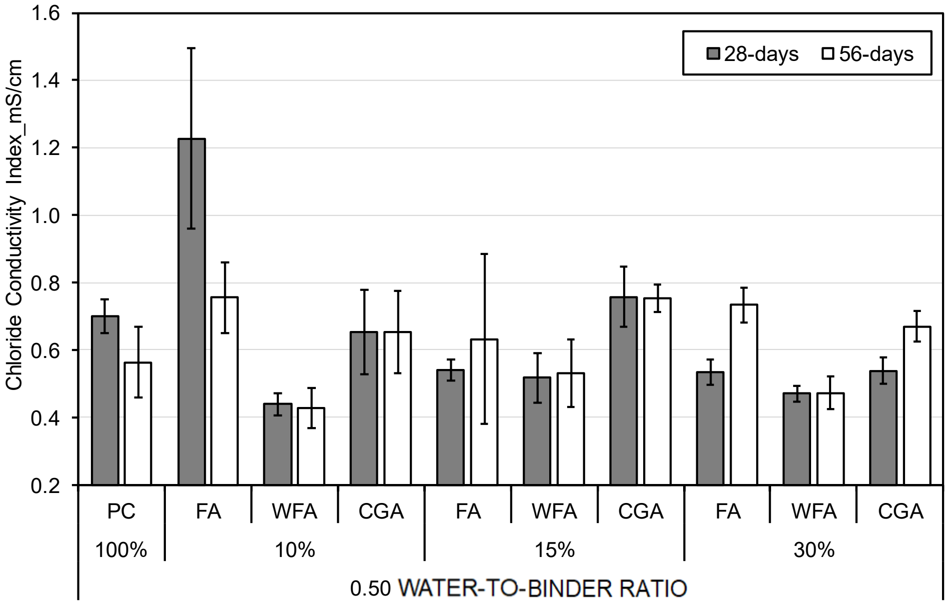

Figure 59: Influence of binder type on the chloride conductivity index results with 0.50 water-to-binder ratio

The 10% WFA-0.60, 10% CGA-0.60 and 30% FA-0.60 concretes had CCI values lower than those observed for the 100% PC-0.60 concretes at 28 and 56-days of testing(Figure 60).

### 4.5.3.2.3 28-days testing age of CCI (w/b = 0.60)

The 15% FA-0.60 and 15% WFA-0.60 concretes had the share the same CCI value which was also witnessed for the 100% PC-0.60 concrete. This means the FA-0.60 and WFA-0.60 concretes did not influence the CCI of concrete, the was neither a deterioration of chloride ingress resistance nor an improvement. The 10% WFA-0.60, 10% CGA-0.60 and 30% FA-

0.60 concretes had CCI values lower than that observed for the 100% PC-0.60 concrete. The 10% CGA-0.60 concrete had the most positive influence on the CCI of concrete, due to low CCI value (Figure 60). There was no significant difference between the 100% PC-0.60 and 15% FA-0.60, 100% PC-0.60 and 15% WFA-0.60, 100% PC-0.60 and 30% FA-0.60, as well as 100% PC-0.60 and 30% WFA-0.60 concretes. There was no significant difference between the 15% FA-0.60 and 15% WFA-0.50 concretes. The statistical details are presented in Appendix F.

#### 4.5.3.2.4 56-days testing age of CCI (w/b = 0.60)

The 10% FA-0.60, 10% WFA-0.60, 10% CGA-0.60, 15% FA-0.60, 15% WFA-0.60 and 30% FA-0.60 concretes had CCI values lower than that of the 100% PC-0.60 concrete. They provide more resistance to chloride ingress than the 100% PC-0.60 concrete. The 10% CGA-0.60 concrete had the most influence on the CCI of concrete, its CCI value was the lowest compared to the 100% PC-0.60 concrete (Figure 60). There was no significant difference between the 100% PC-0.60 and 10% FA-0.60, 100% PC-0.60 and 10% WFA-0.60, 100% PC-0.60 and 15% FA-0.60, 100% PC-0.60 and 15% WFA-0.60, 100% PC-0.60 and 15% CGA-0.60, 100% PC-0.60 and 30% FA-0.60, 100% PC-0.60 and 30% WFA-0.60 as well as 100% PC-0.60 and 30% CGA-0.60 concretes. There was no significant difference between the 10% FA-0.60 and 10% WFA-0.60, 15% FA-0.60 and 15% WFA-0.50, 30% FA-0.60 and 30% WFA-0.50, as well as 30% FA-0.60 and 30% CGA-0.50 concretes. The statistical details are presented in Appendix F.

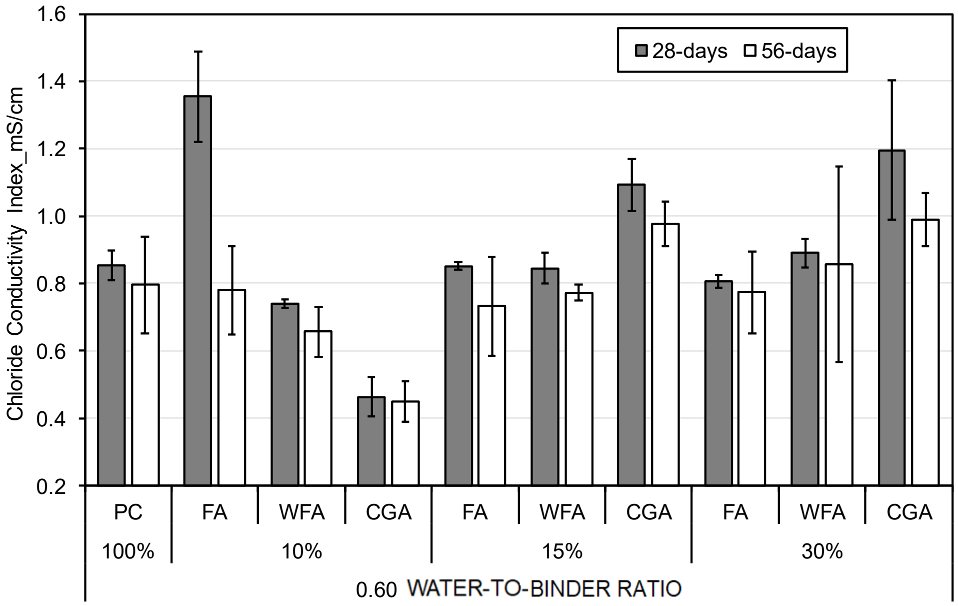

Figure 60: Influence of binder type on the chloride conductivity index results with 0.60 water-to-binder ratio

#### 4.5.3.3 Influence of replacement level on chloride conductivity index

The 10% WFA-0.50, 15% WFA-0.50 and 30% WFA-0.50 concretes had the low CCI values (Figure 61). The 10% WFA-0.50 concrete had the lowest CCI value compared to all the SCM-0.50 concretes. The highest replacement levels for PC were expected to have the low CCI values, as the fines of the SCM occupy the voids in the concrete, densifying the concrete and increasing its resistance to penetrability. This was not the case, this may be due to the internal chemical reactivity of the binder, and more commonly the particle size and shape. The quality of the WFA-0.50 concretes did not improve with age, the same CCI values were observed at 28-days and 56-days of testing. The same observation was made for the 10% CGA-0.50 and 15% CGA-0.50 concrete. The study on the chloride conductivity index of the WFA and CGA concrete beyond 56-days is required to determine whether the quality of concrete improves with age.

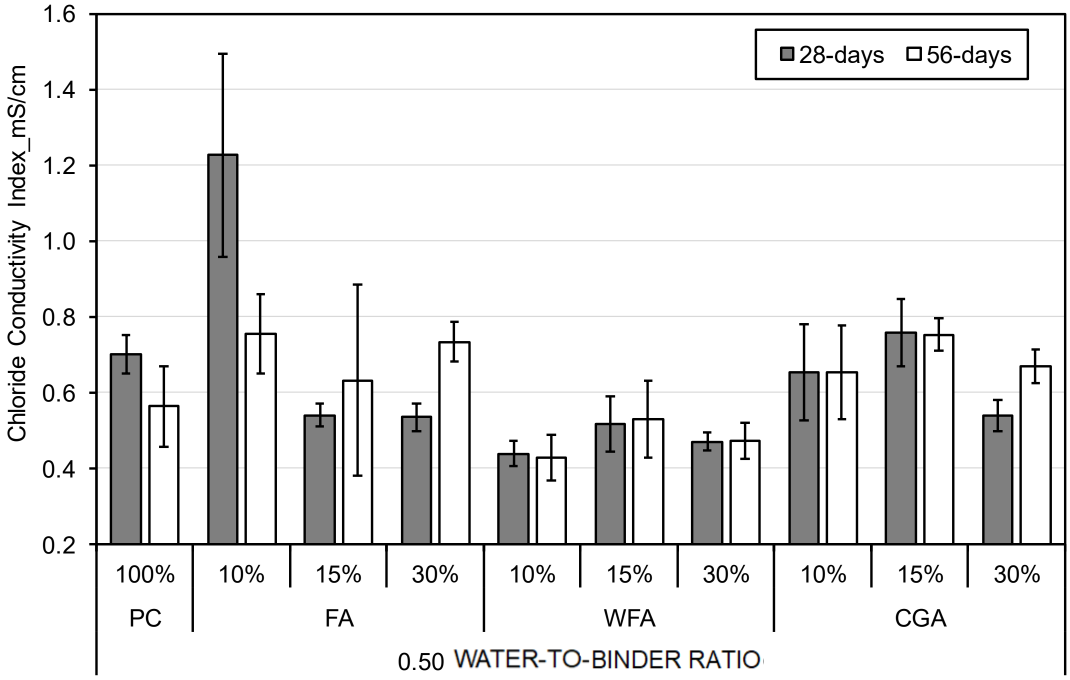

Figure 61: Influence of replacement level on the chloride conductivity index results with 0.50 water-to-binder ratio

At 28-days of testing the CCI values of the FA-0.60 concretes reduced with increasing replacement level for PC (Figure 62), indicating an improvement in the quality of concrete with increasing replacement level. The WFA-0.60 and CGA-0.60 concretes had increasing CCI values with the increasing replacement for PC at both testing ages, implying that the concrete resistance to chloride ingress reduced. The 70 µm particle size and increased water content was considered to be one of the causes for the observation, which should be further investigated. The 10% CGA-0.60 concrete had the lowest CCI value, meaning it improved the durability of concrete the most.

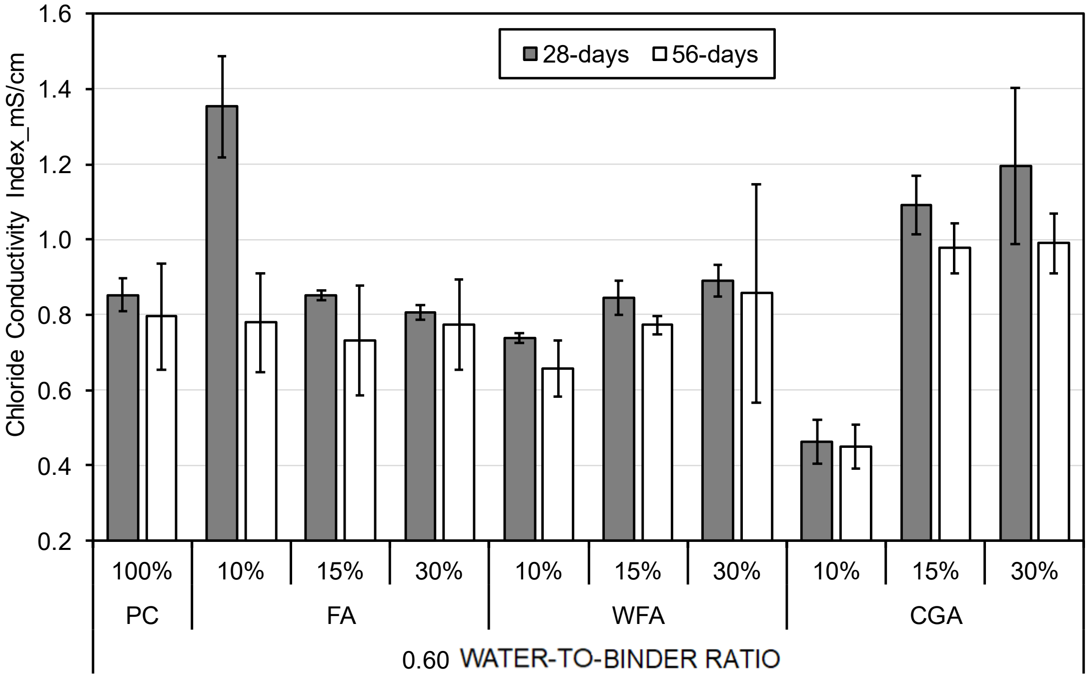

Figure 62: Influence of replacement level on the chloride conductivity index results with 0.60 water-to-binder ratio

## 4.6 Drying Shrinkage Test

The change of shrinkage strain with age is presented using 3-point moving averages. The age zero strain of the mortars was measured 2-days after the curing commenced. The shrinkage strains discussed below should be multiplied by $10^6$. Details on the drying shrinkage strains are presented in Appendix G. Higher SCM replacement levels for the PC mortar, together with a low w/b ratio, resulted in lower shrinkage strains and increased concrete durability, witnessed by a reduction in shrinkage cracks which develop due to drying shrinkage (Zode, 1999; Mehta, 2004). Low shrinkage strain values were observed for the FA-0.50 mortars compared to the FA-0.60 mortars (see Figure 63). The 15% FA-0.60 mortars had similar results with that of the 15% FA-0.50 and 30% FA-0.50 mortars. At 16 days, the drying shrinkage of the 10% FA-0.50 mortar increased but started to decrease 26 days after the shrinkage tests commenced. The 15% FA-0.60 mortar and all the FA-0.50 mortars experienced far less shrinkage than the 100% PC mortar samples. The shrinkage strains of the 10% FA-0.60 and 30% FA-0.60 mortars steadily increased with time until the measured strains exceeded that of the 100% PC-0.50 and 100% PC-0.60 mortars. More shrinkage was expected in the mortars with a w/b ratio of 0.60 and a lower replacement level for PC. In this study, the 10% FA-0.60, 15% FA-0.50 and 30% FA-0.50 conformed to literature (Alexander, 1998; Atis, 2003; Berg & Kukko, 2005).

There was a trend of increasing shrinkage strains for all the CGA mortars. Between 12-days and 24-days of age, the shrinkage strains of the 10% CGA-0.50, 15% CGA-0.50, 30% CGA-0.50 and 10% CGA-0.60 mortars surpassed those of the 100% PC-0.50 and 100% PC-0.60 mortars (Figure 64). The 15% CGA-0.60 and 30% CGA-0.60 mortars, had shrinkage strains lower than those of the 100% PC-0.50 and 100% PC-0.60 mortars, for 14 days but they were gradually increasing. At 24 days 15% CGA-0.60 had a higher shrinkage strain than the 100% PC concretes but on 26 days to 30 days their shrinkage strains were similar and followed a similar trend.

There was a consistent steady increase of shrinkage strains for all the WFA mortars, see Figure 65. The 15% WFA-0.50 mortar shrinkage strains remained below those of 100% PC-0.50 and 100% PC-0.60. Between days 14 and 18, the 30% WFA-0.50, 10% WFA-0.50, 15% WFA-0.60 and 30% WFA-0.60 mortars measured higher shrinkage strains than those of the 100% PC mortars shrinkage strains.

### 4.6.1 Influence of w/b ratio on drying shrinkage

In general, the higher w/b ratio resulted in higher shrinkage strains, this was due to higher porosity and increased interconnectivity of voids (Alexander, 1998; Babu & Prasad, 2012; Owens, 2009). This was very clear from the FA mortars. Comparatively, the influence of the higher w/b ratio on the drying shrinkage of mortars with WFA and CGA was not explicitly different from that of the lower w/b ratio.

### 4.6.2 Influence of binder type on drying shrinkage

The some of the initial shrinkage strains of the CGA mortars were much lower than those of the FA mortars and WFA mortars. There was a noticeable difference in the trends of the mortars due to the wide range of the shrinkage strain increase with age. The FA mortars had lowest shrinkage strains for the first 20 days of testing, excluding the 15% FA-0.60 and 30% FA-0.60 mortars. The shrinkage strains of the 15% FA-0.60 and 30% FA-0.60 mortars were comparable to the CGA mortars. The 10% CGA-0.50 mortar had the highest shrinkage strains for the CGA mortars. The lowest shrinkage strain was witnessed from the 30% CGA-0.50 mortar. The WFA mortars experienced a steadily increasing drying shrinkage strain with age. The 15% WFA-0.50 mortars had the lowest drying shrinkage strains, while the 30% WFA-0.50 had the highest drying shrinkage strains.

### 4.6.3 Influence of replacement level on drying shrinkage

The judgement on whether the shrinkage strains of mortars are low or high was done based on the observed results from the drying shrinkage test. The shrinkage strain of a mortar was low or high relative to shrinkage strains observed from the SCM mortars. Any SCM mortar with drying shrinkage strains surpassing those of the 100% PC mortars was considered high. At 10% replacement level for PC, the SCMs mortars influenced the drying shrinkage differently, the 10% WFA-0.50 mortar had the highest shrinkage strains for 16 days but reduced thereafter. The 10% CGA-0.50 mortar had the highest shrinkage strains throughout the testing ages. The 10% FA-0.50 mortar was among the lowest shrinkage strain measurements but started increasing after 18 days to moderate drying shrinkage strains measurements. At 15% replacement level for PC, the shrinkage strains of the FA, WFA and CGA mortars were considered to be moderate, neither high nor low. At 30% replacement level for PC, the 30% FA and 30% CGA mortars had low shrinkage strains, whilst the WFA mortars had high shrinkage strains.

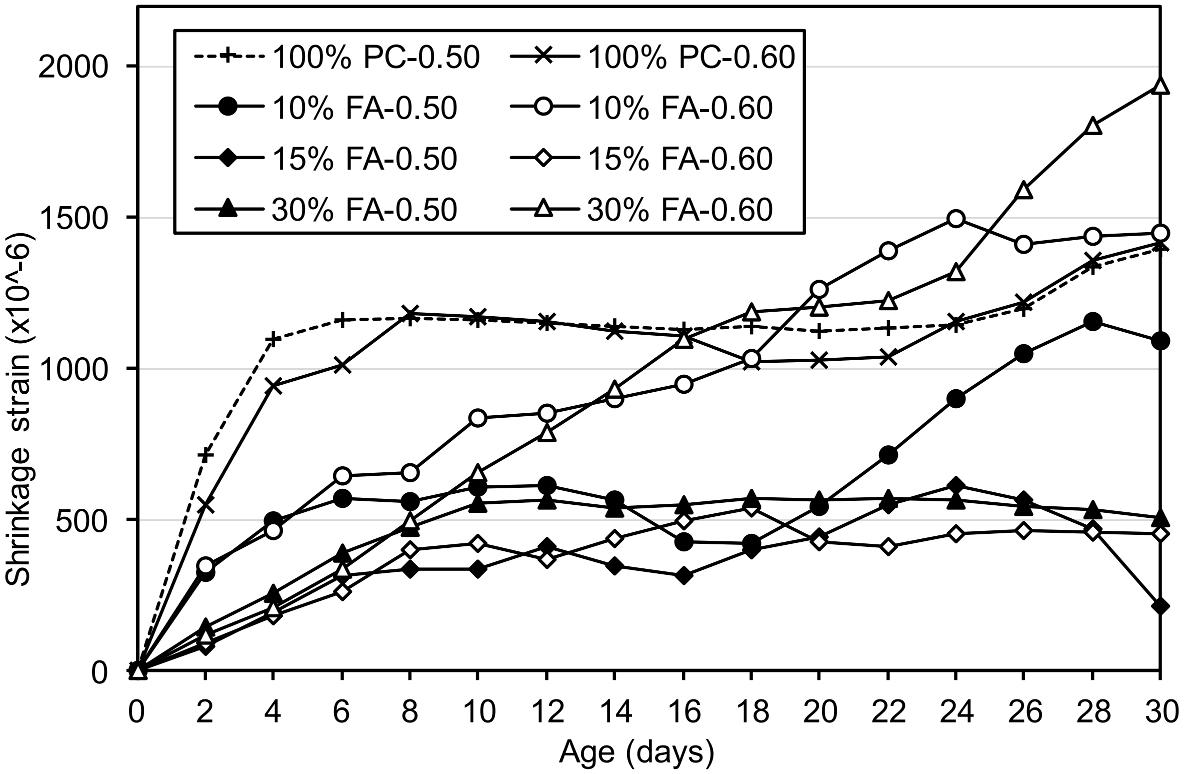

Figure 63: Drying shrinkage results of FA mortars in comparison to PC mortars

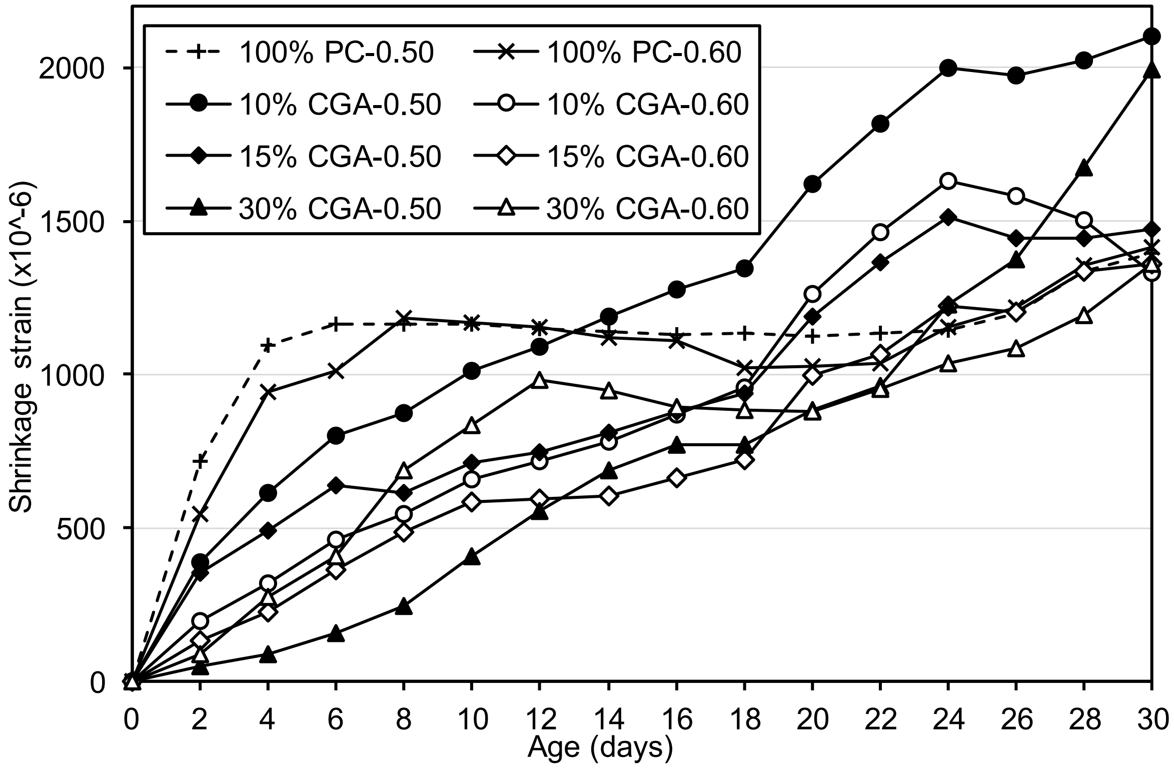

Figure 64: Drying shrinkage results of CGA mortars in comparison to PC mortars

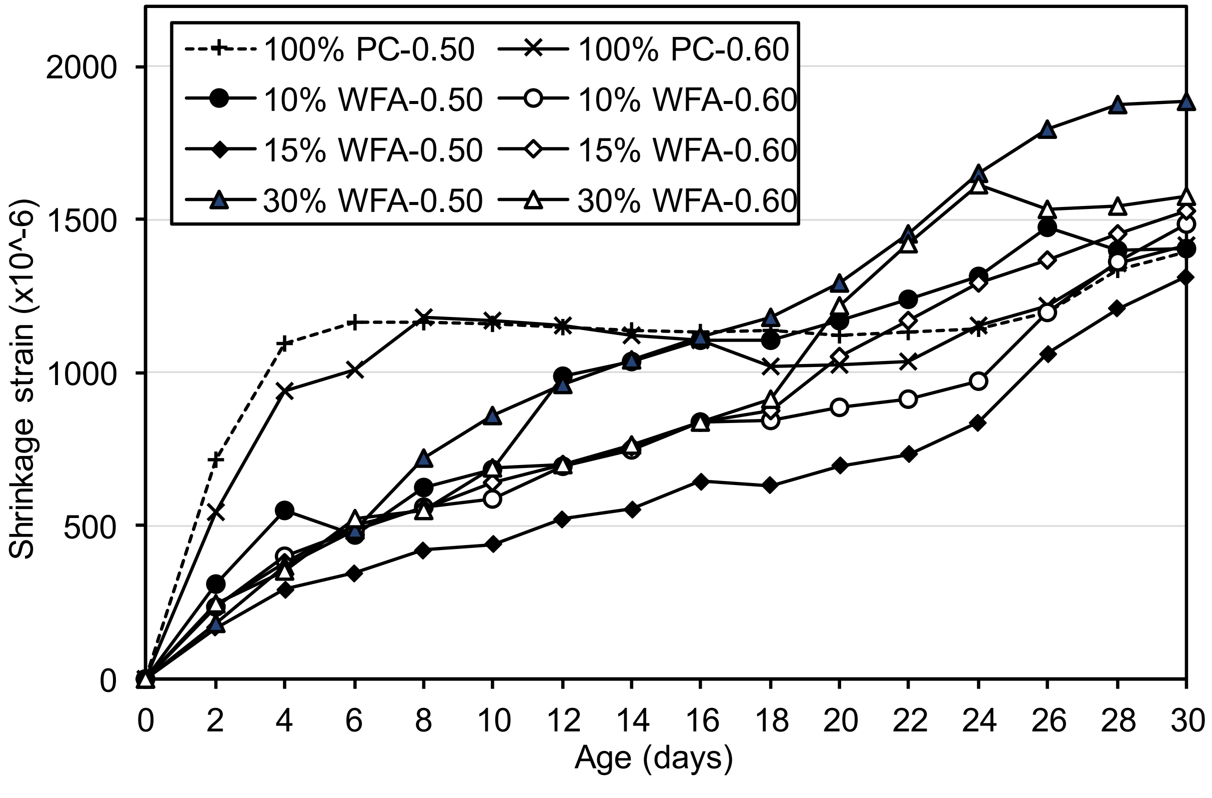

Figure 65: Drying shrinkage results of WFA mortars in comparison to PC mortars

# CHAPTER 5 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The following chapter provides the conclusions based on the results and discussions in Chapter 4. Recommendations are for future and further research are also presented.

The following is a summary of observations from the concrete slump, its compressive strength, and durability test results

a) There was a positive correlation between the slump measurements of the FA and WFA, as well as FA and CGA concrete mixes for both w/b ratios. At all replacement levels for PC with 0.50 w/b ratio, the CGA concrete mix had the highest slump measurements. The slump measurements of the WFA-0.50 and FA-0.50 concrete mixes were similar, as well as those of the WFA-0.60 and FA-0.60 concrete mixes. At 15% replacement level for PC with 0.60 w/b ratio the CGA concrete mix did not have the highest slump measurement, the FA concrete mix had the highest.

b) Most of the WFA concretes compressive strength results and trends were comparable to those of the FA concretes, but from 28 to 56-days of testing the WFA concretes did not surpass the their 28-days strength. The 10% CGA concretes did not have increasing strength with age. Only the 10% FA concretes achieved the 56-days compressive strengths those of the 100% PC concretes.

c) With 0.50 w/b ratio, the tensile strengths of the 10% FA, 10% WFA and 10% CGA concretes were comparable. The 30% FA-0.50 and 30% WFA-0.50, as well as 15% FA-0.60 and 15% WFA-0.60 concretes had the same tensile strength.

d) At both testing ages, the 10% CGA-0.50, 15% CGA-0.50 and 10% CGA-0.60 concretes had the higher OPI values. The OPI values of the 15% FA-0.50 and 15% WFA-0.50, 10% FA-0.60 and 10% WFA-0.60, as well as 15% FA-0.50 and 15% WFA-0.60 concretes are comparable.

e) The WSI values of most of the concretes are too high and indicate poor quality concrete. The 10% FA-0.50 and 30% FA-0.50 concretes at both testing ages had good quality concrete and had the lowest rate of water absorption.

f) The 10% WFA-0.50, 30% WFA-0.50, and 10% CGA-0.60 concretes had the low CCI values, indicating that they improved the resistance of concrete from chloride ingress.

## 5.1 Influence of WFA on concrete strength

The WFA concretes had higher early-age compressive strengths than the FA concretes. The WFA concretes have been highly comparable with the FA concretes at 28-days of testing. The two supplementary cementitious materials exhibited similar influences on the compressive strength of concrete at the same replacement levels. In some cases, the WFA concretes developed slightly higher compressive strengths than the FA concretes, the 15% WFA-0.60 and 30% WFA-0.60 concretes had higher compressive strengths than the 15% FA-0.60 and 30% WFA-0.60 concretes. At 56-days of testing, the 10% WFA-0.50, 10% WFA-0.60, 15% WFA-0.50, 15% WFA-0.60 and 30% WFA-0.50 concretes had compressive strengths lower than those observed at 28-days of testing age. The tensile strengths of the 15% WFA-0.50 and 30% WFA-0.60 concretes were greater than those of the 15% FA-0.50 and 30% FA-0.60 concretes. The 30% FA-0.50 and 15% FA-0.60 concretes had the same tensile strengths as the 30% WFA-0.50 and 15% WFA-0.60 concretes. In general, the WFA concretes have had a positive influence on compressive strengths of concrete. The influence of the WFA concrete on strength have been similar to and at times better than that of the FA concretes at 7 and 28-days of testing. The low 56-days strength should be studied in order to be mitigated. The strengths of the WFA concretes are comparable to those of the FA concrete, even though FA is finer.

## 5.2 Influence of WFA on concrete durability

The OPI values of the FA-0.50 concretes were higher than those of the WFA-0.50 at 10%, 15% and 30% replacement level for PC. The OPI values for both the FA and WFA concretes were indicative of good quality concrete, between 9.5 and 10. The 10% FA-0.60 and 10% WFA-0.60 concretes had similar OPI values. The OPI values of the 15% WFA-0.60 and 30% WFA-0.60 concretes were higher than those of the 15% FA-0.50 and 30% FA-0.60 concretes. The 15% WFA-0.60 and 30% FA-0.60 concretes had OPI values indicative of excellent quality concrete, greater than 10.

Most of the WSI values of the FA-0.50, FA-0.60, WFA-0.50 and WFA-0.60 concretes were indicative of poor-quality concrete, between 10 to 15 mm/hr$^{0.5}$. It is understood that the water sorptivity test is highly sensitive to the micro-structure, cracks and voids, in the concrete. The 10% FA-0.50, 15% FA-0.50 and 30% FA-0.50 concretes had lower WSI values than WFA-0.50 concretes. The WSI values of the 10% WFA-0.50 and 15% WFA-0.50 concretes reduced with age, indicating an improvement in the resistance of water penetrability. The 10% FA-0.60, 15% FA-0.60 and 30% FA-0.60 concretes had lower WSI values than the WFA-0.60

concretes. The WSI values of the WFA-0.60 concretes reduced with increasing replacement levels for PC.

The 10% WFA-0.50, 15% WFA-0.50 and 30% WFA-0.50 concretes had the lowest CCI values than the FA-0.50 concretes. The quality of concrete remained the same with age. The quality of the WFA-0.50 concretes were classified as excellent quality as the CCI values were below 0.75 mS/cm. The 10% WFA-0.60 and 30% WFA-0.60 concretes had comparable results to the 10% FA-0.60 and 30% WFA-0.60 concretes.

## 5.3 Influence of CGA on concrete strength

Early-age compressive strengths of the CGA concretes were higher than those of the FA concretes. The 28-days compressive strength of the 15% CGA-0.50, 15% FA-0.60 and 30% CGA-0.50 concretes were lower than those of the 15% FA-0.50, 15% FA-0.60 and 30% FA-0.50 concretes. At 56-days of testing, the compressive strengths of the 15% CGA-0.50 and 30% CGA-0.50 concretes were comparable to those of the 15% FA-0.50 and 30% FA-0.50 concretes. The compressive strength of the 10% CGA-0.60 concrete was lower than that observed at 28-days of testing. The tensile strengths of the 10% CGA-.50, 15% CGA-0.50 30% CGA-0.50 and 30% CGA-0.60 concretes were greater than those of the FA concretes. The 10% CGA-0.50, 30% CGA-0.50 and 30% CGA-0.60 concretes had higher tensile strengths than the 10% FA-0.50, 30% CGA-0.50 and 30% CGA-0.60.

## 5.4 Influence of CGA on concrete durability

The OPI values 10% CGA-0.50 and 15% CGA-0.50 were higher than those of 10% FA-0.50 and 15% FA-0.50. The concrete quality of CGA-0.50 and CGA-0.60 were classified as excellent because the OPI values were above 10. 10% CGA-0.60 had higher OPI values than 10% FA-0.60. 15% CGA-0.60 and 30% CGA-0.60 had similar OPI values as 15% FA-0.60 and 30% FA-0.60, but 30% FA-0.60 improved with age and 30% CGA-0.60 deteriorated with age. Most of the WSI values of FA-0.50, FA-0.60, CGA-0.50 and CGA-0.60 concretes were indicative of poor-quality concrete, between 10 to 15 mm/hr$^{0.5}$. It is understood that the water sorptivity test is highly sensitive to the micro-structure, cracks and voids, in concrete. 10% FA-0.50, 15% FA-0.50 and 30% FA-0.50 had lower WSI values than CGA-0.50 concretes. The WSI values of 10% CGA-0.50 and 30% CGA-0.50 reduced with age, indicating an improvement in the resistance of water penetrability. At 56-days of testing, 10% CGA-0.60 and 30% CGA-0.60 had the same WSI value as 10% FA-0.60. 10% CGA-0.50 and 10% CGA-0.60 had lower CCI values than 10% FA-0.50 and 10% CGA-0.60. 30% CGA-0.50 had the same CCI values as 30% FA-0.50.

## 5.5 Comparison between WFA and CGA

The compressive strengths of all the WFA-0.50 and most of the WFA-0.60 concretes were higher than those of all the CGA-0.50 and most of the CGA-0.60 concretes at 7 and 28-days of testing. At 56-days of testing, the compressive strengths of the 10% WFA-0.50, 10% WFA-0.60, 15% WFA-0.50, 15% WFA-0.60 and 30% WFA-0.50 concretes were lower than those observed at 28-days of testing. The 10% WFA-0.50 and 30% WFA-0.50 concretes had lower tensile strengths than those observed for the 10% CGA-0.50 and 30% CGA-0.60 concretes. The 10% CGA-0.60 and 30% CGA-0.60 concretes had greater tensile strengths than the 10% WFA-0.60 and 30% CGA-0.60 concretes. The CGA-0.50 concretes had higher OPI values than the WFA-0.50 concretes, implying that the CGA-0.50 concretes were less permeable than the WFA-0.50 concretes. The 15% WFA-0.60 and 15% CGA-0.60 concretes had the same OPI values. The WFA and CGA concretes had WSI values indicative of poor quality, at 0.50 and 0.60 w/b ratio, the lowest WSI values were observed from the CGA concretes. The WFA concretes had CCI values lower than most of those witnessed for the CGA concrete, suggesting that the WFA concretes had better quality than the CGA concretes. The WFA concretes had better resistance to chloride ingress than the CGA concretes.

## 5.6 General conclusion

WFA and CGA have a high potential of being used as partial PC replacement in concrete. The replacement for PC with CGA had the most impact on the strength of concrete. The replacement for PC with the 15% CGA also had a positive influence on the concrete compressive strength. At 56-days of testing, the 15% CGA concretes had a comparable strength to that of the 15% FA concretes. It is possible that if the testing age is extended beyond 56-days, the compressive strengths of the 15% CGA concretes could exceed those of the 15% FA and 100% PC concretes. WFA had the most positive influence on the durability of the concrete. In most cases, the 10% WFA and 30% WFA replacement levels for PC significantly improved the durability of concrete. There were several things uncovered about the influence of WFA and CGA on the strength and durability of concrete which have raised questions and led to a list of recommendations for further studies.

## 5.7 Recommendations

This investigation has provided an insight into the possible use of Sasol ashes as SCMs in concrete. However, further research is necessary to fully assess the performance of these materials in concrete. Some areas which need further research may include:

a) A further investigation into the compressive strength development characteristics of CGA and WFA binders. This will aid in understanding why there was a reduction in the 56-day compressive strength of the 10% CGA-0.50 and the 10% WFA-0.50, 15% WFA-0.50, 30% WFA-0.50, 10% WFA-0.60 and 15% WFA-0.60 concretes.
b) The optimum percentage PC replacement in the PC/CGA and PC/WFA needs to be determined.
c) A detailed chemical analysis and determination of the physical characteristics of CGA and WFA binders needs to be undertaken. These analyses will provide vital inform on the extent of similarities between CGA, WFA and FA and also identify factors which influence the performance of the CGA and WFA concretes.
d) This investigation only considered two w/b ratios. A wider w/b ratio range could be investigated in order to assess the performance of the supplementary cementitious materials in these conditions.
e) The impact of increasing the percentage replacement of WFA and CGA in concrete on the concrete strength and durability properties should be further investigated.
f) A prolonged curing period (beyond the 56 days used in this study) could be used in further investigations. This will help assess the influence of the curing duration on the concrete properties. A 90-day curing duration, which is recommended for most laboratory tests involving SCMs in concrete, could be used in further investigations.
g) There is a need to investigate the effect of the WFA and CGA particle sizes on the concrete performance.
h) A ternary blend of CGA, WFA and PC could be investigated.

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# APPENDIX A – SLUMP TEST

Table 16: Slump measurements of PC, FA, CGA and WFA for 0.50 w/b ratio

| **Portland cement** | **100% PC** | **45 mm** |
|---|---|---|

| | **Fly ash** | **Coal gasification ash** | **Weathered fly ash** |
|---|---|---|---|
| *10% replacement level for PC* | 40 mm | 65 mm | 55 mm |
| *15% replacement level for PC* | 55 mm | 55 mm | 50 mm |
| *30% replacement level for PC* | 65 mm | 85 mm | 55 mm |

Table 17: Slump measurement of PC, FA, CGA and WFA for 0.60 w/b ratio

| **Portland cement** | **100% PC** | **85 mm** |
|---|---|---|

| | **Fly ash** | **Coal gasification ash** | **Weathered fly ash** |
|---|---|---|---|
| *10% replacement level for PC* | 85 mm | 105 mm | 80 mm |
| *15% replacement level for PC* | 110 mm | 70 mm | 95 mm |
| *30% replacement level for PC* | 90 mm | 140 mm | 75 mm |

# APPENDIX B – COMPRESSIVE STRENGTH

Table 18: Compressive strength results and statistical analysis of 100% PC-0.50 vs FA-0.50

| | **100% PC** | | | **10% FA** | | | **15% FA** | | | **30% FA** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| days | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** |
| 1 | 53 | 63 | 67 | 50 | 59 | 67 | 41 | - | 65 | 31 | 46 | 50 |
| 2 | 53 | 63 | - | 51 | 60 | 70 | 44 | 55 | 64 | 31 | 42 | 52 |
| 3 | 51 | 64 | 69 | 46 | 60 | 66 | 44 | 56 | 59 | 32 | 45 | 55 |
| **average** | 53 | 63 | 67 | 49 | 60 | 68 | 43 | 56 | 63 | 31 | 44 | 53 |
| **Std. dev.** | 0.61 | 0.70 | 1.27 | 2.23 | 0.49 | 1.81 | 1.26 | 0.80 | 2.47 | 0.63 | 1.40 | 1.98 |
| **Min.** | 51 | 61 | 63 | 43 | 58 | 63 | 40 | 54 | 57 | 30 | 41 | 48 |
| **Max.** | 54 | 65 | 70 | 54 | 61 | 72 | 46 | 58 | 69 | 33 | 48 | 58 |
| **95% range** | 1.52 | 1.73 | 3.16 | 5.54 | 1.21 | 4.51 | 3.13 | 1.99 | 6.13 | 1.57 | 3.48 | 4.91 |
| **p-value PC** | | | | 0.1515 | 0.0051 | 0.9798 | 0.0028 | 0.0206 | 0.1029 | 0.0000 | 0.0005 | 0.0050 |

Table 19: Compressive strength results and statistical analysis of 100% PC-0.6 vs FA-0.60

| | **100% PC** | | | **10% FA** | | | **15% FA** | | | **30% FA** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| days | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** |
| 1 | - | 52 | - | 33 | 50 | 57 | 26 | 35 | 42 | 21 | 34 | 40 |
| 2 | 42 | 51 | 56 | 31 | 49 | - | 25 | - | - | 22 | 35 | - |
| 3 | 41 | - | 51 | 33 | 51 | 60 | 27 | 37 | 43 | 21 | 35 | 42 |
| average | 41 | 52 | 56 | 32 | 50 | 59 | 26 | 36 | 42 | 21 | 34 | 41 |
| Std. dev. | 0.36 | 0.75 | 2.49 | 0.75 | 0.73 | 1.72 | 0.52 | 0.70 | 0.35 | 0.59 | 0.54 | 1.08 |
| Min. | 41 | 50 | 50 | 30 | 48 | 54 | 25 | 34 | 41 | 20 | 33 | 38 |
| Max. | 42 | 53 | 62 | 34 | 52 | 63 | 27 | 38 | 43 | 23 | 36 | 44 |
| 95% range | 0.89 | 1.86 | 6.19 | 1.86 | 1.81 | 4.27 | 1.30 | 1.74 | 0.87 | 1.47 | 1.34 | 2.68 |
| p-value PC | | | | 0.0009 | 0.2879 | 0.2511 | 0.0002 | 0.0044 | 0.1332 | 0.0001 | 0.0075 | 0.0870 |

Table 20: Compressive strength results and statistical analysis of 100% PC-0.50 vs CGA-0.50

| | **100% PC** | | | **10% CGA** | | | **15% CGA** | | | **30% CGA** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| days | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** |
| 1 | 53 | 63 | 67 | 47 | - | - | 43 | 50 | 60 | 36 | - | 49 |
| 2 | 53 | 63 | - | 48 | 47 | 46 | 44 | 53 | 60 | 34 | 45 | 52 |
| 3 | 51 | 64 | 69 | 48 | 42 | 43 | 43 | 52 | 62 | 36 | 40 | 53 |
| **average** | 53 | 63 | 67 | 48 | 44 | 45 | 43 | 51 | 61 | 35 | 43 | 51 |
| **Std. dev.** | 0.61 | 0.70 | 1.27 | 0.59 | 2.30 | 1.57 | 0.52 | 1.19 | 1.06 | 0.86 | 2.73 | 1.35 |
| **Min.** | 51 | 61 | 63 | 46 | 39 | 41 | 42 | 48 | 58 | 33 | 36 | 48 |
| **Max.** | 54 | 65 | 70 | 49 | 50 | 49 | 45 | 54 | 64 | 37 | 49 | 55 |
| **95% range** | 1.52 | 1.73 | 3.16 | 1.46 | 5.71 | 3.90 | 1.28 | 2.95 | 2.63 | 2.13 | 6.78 | 3.35 |
| **p-value PC** | | | | 0.0014 | 0.0656 | 0.0089 | 0.0001 | 0.0008 | 0.0575 | 0.000048 | 0.0749 | 0.0076 |
| **p-value FA** | | | | 0.5010 | 0.0886 | 0.0047 | 0.6691 | 0.0399 | 0.4091 | 0.0083 | 0.6285 | 0.0806 |

Table 21: Compressive strength results and statistical analysis of 100% PC-0.6 vs CGA-0.60

| | **100% PC** | | | **10% CGA** | | | **15% CGA** | | | **30% CGA** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| days | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** |
| 1 | - | 52 | - | 36 | - | 44 | 33 | 42 | - | - | 31 | 38 |
| 2 | 41 | 51 | 56 | 36 | 45 | - | 35 | 41 | 47 | 22 | 28 | 38 |
| 3 | 41 | - | 51 | 35 | 45 | 45 | - | 42 | 46 | 23 | - | 37 |
| **average** | 41 | 52 | 56 | 36 | 45 | 45 | 34 | 42 | 46 | 22 | 29 | 38 |
| **Std. dev.** | 0.36 | 0.75 | 2.49 | 0.31 | 0.05 | 0.28 | 0.80 | 0.60 | 0.10 | 0.54 | 1.54 | 0.20 |
| **Min.** | 41 | 50 | 50 | 35 | 45 | 44 | 32 | 40 | 46 | 21 | 26 | 37 |
| **Max.** | 42 | **53** | 62 | 36 | 45 | 45 | 36 | 43 | 47 | 24 | 33 | 38 |
| **95% range** | 0.89 | 1.86 | 6.19 | 0.77 | 0.12 | 0.70 | 1.99 | 1.49 | 0.25 | 1.34 | 3.83 | 0.51 |
| **p-value PC** | | | | 0.0098 | 0.0741 | 0.1693 | 0.0388 | 0.0144 | 0.2185 | 0.0024 | 0.0180 | 0.0985 |
| **p-value FA** | | | | 0.0133 | 0.0099 | 0.0713 | 0.030 | 0.0272 | 0.0378 | 0.2077 | 0.1762 | 0.1890 |

Table 22: Compressive strength results and statistical analysis of 100% PC-0.50 vs WFA-0.50

| | **100% PC** | | | **10% WFA** | | | **15% WFA** | | | **30% WFA** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| days | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** |
| 1 | 53 | 63 | 67 | 53 | 58 | - | 44 | 56 | - | 37 | 45 | - |
| 2 | 53 | 63 | - | 53 | 62 | 49 | 44 | 55 | 33 | 39 | - | 45 |
| 3 | 51 | 64 | 69 | 51 | 61 | 47 | 44 | 56 | 35 | 37 | 47 | 42 |
| **average** | 53 | 63 | 67 | 52 | 60 | 48 | 44 | 56 | 34 | 38 | 46 | 43 |
| **Std. dev.** | 0.61 | 0.70 | 1.27 | 0.61 | 1.59 | 0.96 | 0.23 | 0.53 | 1.17 | 1.15 | 1.05 | 1.74 |
| **Min.** | 51 | 61 | 63 | 51 | 56 | 45 | 44 | 54 | 31 | 35 | 44 | 39 |
| **Max.** | 54 | 65 | 70 | 54 | 64 | 50 | 45 | 57 | 37 | 41 | 49 | 48 |
| **95% range** | 1.52 | 1.73 | 3.16 | 1.52 | 3.94 | 2.38 | 0.57 | 1.33 | 2.91 | 2.87 | 2.61 | 4.32 |
| **p-value PC** | | | | 1.0000 | 0.0815 | 0.0081 | 0.0010 | 0.0003 | 0.0027 | 0.0005 | 0.0148 | 0.0104 |
| **p-value FA** | | | | 0.1515 | 0.7687 | 0.0011 | 0.2800 | 0.8536 | 0.0009 | 0.0058 | 0.2663 | 0.0434 |

Table 23: Compressive strength results and statistical analysis of 100% PC-0.6 vs WFA-0.60

| | **100% PC** | | | **10% WFA** | | | **15% WFA** | | | **30% WFA** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| days | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** | **7** | **28** | **56** |
| 1 | - | 52 | - | 40 | 50 | 43 | 32 | 39 | 32 | 28 | 37 | 43 |
| 2 | 41 | 51 | 56 | 41 | 51 | 47 | 33 | 41 | - | 28 | 34 | 42 |
| 3 | 41 | - | 51 | 40 | 51 | 43 | 32 | 42 | 36 | 29 | 36 | 43 |
| **average** | 41 | 52 | 56 | 40 | 51 | 44 | 32 | 41 | 34 | 28 | 36 | 42 |
| **Std. dev.** | 0.36 | 0.75 | 2.49 | 0.47 | 0.55 | 2.06 | 0.46 | 1.02 | 1.88 | 0.42 | 1.30 | 0.45 |
| **Min.** | 41 | 50 | 50 | 39 | 49 | 39 | 31 | 38 | **29** | 27 | 33 | 41 |
| **Max.** | 42 | **53** | 62 | 41 | 52 | 50 | 33 | 43 | 39 | 29 | 39 | 43 |
| **95% range** | 0.89 | 1.86 | 6.19 | 1.17 | 1.37 | 5.13 | 1.14 | 2.52 | 4.67 | 1.03 | 3.22 | 1.11 |
| **p-value PC** | | | | 0.1949 | 0.3853 | 0.1078 | 0.0011 | 0.0035 | 0.0295 | 0.0006 | 0.0011 | 0.1361 |
| **p-value FA** | | | | 0.000596 | 0.6552 | 0.0163 | 0.0002 | 0.0218 | 0.1333 | 0.0003 | 0.2080 | 0.4245 |

# APPENDIX C – TENSILE STRENGTH

Table 24: Tensile splitting strength results and statistical analysis with 0.50 and 0.60 w/b ratio for 100% PC concrete vs FA concrete

| | **0.50 water/binder ratio_28-days testing age** | | | | **0.60 water/binder ratio_28-days testing age** | | | |
|---|---|---|---|---|---|---|---|---|
| | **100% PC** | **10% FA** | **15% FA** | **30% FA** | **100% PC** | **10% FA** | **15% FA** | **30% FA** |
| 1 | 5.1 | 6.6 | - | 5.9 | 6.3 | 6.0 | 4.4 | 4.0 |
| 2 | 5.3 | 6.6 | 5.2 | 6.0 | - | - | - | - |
| 3 | 5.1 | - | 5.9 | - | 5.5 | 6.4 | 4.1 | 3.9 |
| **average** | 5.1 | 6.6 | 5.5 | 5.9 | 5.9 | 6.2 | 4.3 | 3.9 |
| **Std. dev.** | 0.11 | 0.03 | 0.37 | 0.04 | 0.40 | 0.22 | 0.14 | 0.05 |
| **Min.** | 4.9 | 6.5 | 4.6 | 5.8 | 4.9 | 5.7 | 3.9 | 3.8 |
| **Max.** | 5.4 | 6.7 | 6.4 | 6.0 | 6.9 | 6.7 | 4.6 | 4.0 |
| **95% range** | 0.28 | 0.07 | 0.92 | 0.10 | 0.99 | 0.55 | 0.35 | 0.12 |
| **p-value PC** | | 0.0012 | 0.4785 | 0.0042 | | 0.5733 | 0.1223 | 0.1217 |

Table 25: Tensile splitting strength results and statistical analysis with 0.50 and 0.60 w/b ratio for 100% PC concrete vs CGA concrete

| | **0.50 water/binder ratio_28-days testing age** | | | | **0.60 water/binder ratio_28-days testing age** | | | |
|---|---|---|---|---|---|---|---|---|
| | **100% PC** | **10% CGA** | **15% CGA** | **30% CGA** | **100% PC** | **10% CGA** | **15% CGA** | **30% CGA** |
| 1 | 5.1 | - | 5.7 | 6.6 | 6.3 | - | 4.0 | 5.0 |
| 2 | 5.3 | 7.0 | 5.9 | 7.3 | - | 3.9 | 4.0 | 5.9 |
| 3 | 5.1 | 6.5 | - | - | 5.5 | 4.6 | 3.6 | - |
| **average** | 5.1 | 6.8 | 5.8 | 6.9 | 5.9 | 4.2 | 3.8 | 5.5 |
| **Std. dev.** | 0.11 | 0.24 | 0.08 | 0.34 | 0.40 | 0.38 | 0.18 | 0.4 |
| **Min.** | 4.9 | 6.2 | 5.6 | 6.1 | 4.9 | 3.3 | 3.4 | 4.4 |
| **Max.** | 5.4 | 7.4 | 6.0 | 7.7 | 6.9 | 5.2 | 4.3 | 6.5 |
| **95% range** | 0.28 | 0.60 | 0.20 | 0.84 | 0.99 | 0.94 | 0.45 | 1.02 |
| **p-value PC** | | 0.0674 | 0.0128 | 0.1064 | | 0.0953 | 0.0973 | 0.5144 |
| **p-value FA** | | 0.6071 | 0.5748 | 0.2085 | | 0.0679 | 0.1392 | 0.1611 |

Table 26: Tensile splitting strength results and statistical analysis with 0.50 and 0.60 w/b ratio for 100% PC concrete vs WFA concrete

| | **0.50 water/binder ratio_28-days testing age** | | | | **0.60 water/binder ratio_28-days testing age** | | | |
|---|---|---|---|---|---|---|---|---|
| | **100% PC** | **10% WFA** | **15% WFA** | **30% WFA** | **100% PC** | **10% WFA** | **15% WFA** | **30% WFA** |
| 1 | 5.1 | - | 6.7 | 6.0 | 6.3 | 3.5 | 5.1 | 4.6 |
| 2 | 5.3 | 6.7 | - | - | - | 3.9 | - | 4.2 |
| 3 | 5.1 | 6.0 | 6.6 | 5.4 | 5.5 | 4.0 | 4.4 | - |
| **average** | 5.14 | 6.3 | 6.7 | 5.7 | 5.9 | 3.8 | 4.8 | 4.4 |
| **Std. dev.** | 0.11 | 0.33 | 0.04 | 0.32 | 0.40 | 0.22 | 0.35 | 0.22 |
| **Min.** | 49 | 5.5 | 6.6 | 4.9 | 4.9 | 3.2 | 3.9 | 3.8 |
| **Max.** | 5.4 | 7.1 | 6.8 | 6.5 | 6.9 | 4.3 | 5.6 | 4.9 |
| **95% range** | 0.28 | 0.82 | 0.10 | 0.79 | 0.99 | 0.55 | 0.87 | 0.55 |
| **p-value PC** | | 0.1556 | 0.0007 | 0.3075 | | 0.1896 | 0.1696 | 0.1129 |
| **p-value FA** | | 0.5515 | 0.1946 | 0.6440 | | 0.1564 | 0.3631 | 0.2558 |

# APPENDIX D – OXYGEN PERMEABILITY INDEX

Table 27: 28 Days: Oxygen permeability index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.50 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | OPI | 10.0 | 10.1 | 10.1 | 10.2 | 10.1 | 0.04 | 10.0 | 10.2 | 0.07 | | |
| **90PC /10FA** | OPI | 10.0 | 10.0 | - | 10.0 | 10.0 | 0.00 | 10.0 | 10.0 | 0.01 | 0.033 | |
| **85PC /15FA** | OPI | 9.7 | 9.9 | 9.7 | 9.8 | 9.8 | 0.10 | 9.6 | 9.9 | 0.15 | 0.005 | |
| **70PC /30FA** | OPI | 10.1 | 10.2 | 10.2 | 10.0 | 10.1 | 0.08 | 10.0 | 10.3 | 0.13 | 0.600 | |
| **90PC /10WFA** | OPI | 9.4 | 9.9 | 9.6 | 9.9 | 9.7 | 0.21 | 9.4 | 10. | 0.33 | 0.048 | 0.100 |
| **85PC /15WFA** | OPI | 9.8 | 9.9 | 9.7 | - | 9.8 | 0.09 | 9.7 | 9.9 | 0.14 | 0.026 | 0.758 |
| **70PC /30WFA** | OPI | 9.5 | 9.8 | 9.4 | 9.7 | 9.6 | 0.14 | 9.4 | 9.8 | 0.22 | 0.006 | 0.003 |
| **90PC /10CGA** | OPI | 10.2 | 10.4 | - | 10.1 | 10.2 | 0.10 | 10.1 | 10.4 | 0.16 | 0.160 | 0.075 |
| **85PC /15CGA** | OPI | 10.5 | 10.3 | 10.2 | 10.7 | 10.4 | 0.20 | 10.1 | 10.7 | 0.32 | 0.078 | 0.007 |
| **70PC /30CGA** | OPI | 9.8 | 9.6 | - | 9.4 | 9.6 | 0.14 | 9.4 | 9.8 | 0.22 | 0.030 | 0.018 |

Table 28: 56 Days: Oxygen permeability index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.50 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | OPI | 10.0 | 10.1 | 10.1 | 10.1 | 10.1 | 0.04 | 10.1 | 10.1 | 0.06 | | |
| **90PC /10FA** | OPI | - | 10.0 | 9.8 | 10.0 | 9.9 | 0.11 | 9.8 | 10.1 | 0.17 | 0.154 | |
| **85PC /15FA** | OPI | 9.9 | 9.9 | 9.6 | 9.8 | 9.8 | 0.09 | 9.7 | 9.9 | 0.14 | 0.007 | |
| **70PC /30FA** | OPI | 10.0 | 10.2 | 10.1 | 10.0 | 10.1 | 0.08 | 10.0 | 10.2 | 0.12 | 0.887 | |
| **90PC /10WFA** | OPI | 9.4 | - | 9.6 | 9.9 | 9.6 | 0.19 | 9.3 | 9.9 | 0.30 | 0.072 | 0.149 |
| **85PC /15WFA** | OPI | 9.8 | 9.9 | 9.7 | - | 9.8 | 0.09 | 9.7 | 9.9 | 0.15 | 0.037 | 0.963 |
| **70PC /30WFA** | OPI | 9.7 | 9.6 | 9.3 | 9.7 | 9.6 | 0.15 | 9.3 | 9.8 | 0.24 | 0.009 | 0.006 |
| **90PC /10CGA** | OPI | 10.2 | 10.1 | - | 10.1 | 10.2 | 0.05 | 10.1 | 10.2 | 0.09 | 0.201 | 0.070 |
| **85PC /15CGA** | OPI | 10.5 | 10.3 | 10.1 | 10.6 | 10.4 | 0.19 | 10.1 | 10.7 | 0.31 | 0.070 | 0.007 |
| **70PC /30CGA** | OPI | 10.3 | 10.2 | - | 10.1 | 10.2 | 0.08 | 10.1 | 10.3 | 0.12 | 0.163 | 0.159 |

Table 29: 28 days: Oxygen permeability index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.60 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | OPI | 10.0 | 10.1 | 10.1 | 10.2 | 10.1 | 0.04 | 10.0 | 10.2 | 0.06 | | |
| **90PC /10FA** | OPI | 9.9 | - | 9.9 | 9.8 | 9.9 | 0.07 | 9.8 | 10.0 | 0.12 | 0.032 | |
| **85PC /15FA** | OPI | 10.0 | 9.9 | 9.9 | 9.9 | 9.9 | 0.04 | 9.9 | 10.0 | 0.06 | 0.001 | |
| **70PC /30FA** | OPI | 9.9 | 10.1 | 10.1 | 9.9 | 10.0 | 0.09 | 9.9 | 10.1 | 0.14 | 0.166 | |
| **90PC /10WFA** | OPI | 9.9 | 9.9 | 9.8 | 9.8 | 9.8 | 0.08 | 9.7 | 10.0 | 0.13 | 0.007 | 0.653 |
| **85PC /15WFA** | OPI | 10.1 | 10.1 | 10 | 9.8 | 10.0 | 0.13 | 9.8 | 10.2 | 0.20 | 0.261 | 0.346 |
| **70PC /30WFA** | OPI | 10.3 | 10.2 | 10.2 | - | 10.2 | 0.05 | 10.2 | 10.3 | 0.07 | 0.021 | 0.010 |
| **90PC /10CGA** | OPI | 10.3 | 10.3 | 10.2 | 10.3 | 10.3 | 0.06 | 10.2 | 10.4 | 0.10 | 0.010 | 0.003 |
| **85PC /15CGA** | OPI | 10.0 | - | 10.0 | 10.0 | 10.0 | 0.01 | 10.0 | 10.0 | 0.02 | 0.063 | 0.007 |
| **70PC /30CGA** | OPI | 9.9 | 10.0 | - | 10.1 | 10.0 | 0.08 | 9.9 | 10.2 | 0.13 | 0.342 | 0.795 |

Table 30: 56 days: Oxygen permeability index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.60 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | OPI | 10.2 | 10.3 | 10.1 | 10.2 | 10.2 | 0.06 | 10.1 | 10.3 | 0.10 | | |
| **90PC /10FA** | OPI | 9.9 | - | 9.9 | 9.7 | 9.8 | 0.07 | 9.7 | 9.9 | 0.12 | 0.004 | |
| **85PC /15FA** | OPI | 9.9 | 10.0 | 9.9 | 10.0 | 10.0 | 0.06 | 9.9 | 10.0 | 0.09 | 0.002 | |
| **70PC /30FA** | OPI | 10.0 | 10.1 | 10.0 | - | 10.0 | 0.03 | 10 | 10.1 | 0.04 | 0.007 | |
| **90PC /10WFA** | OPI | - | 9.9 | 9.8 | 9.8 | 9.9 | 0.05 | 9.8 | 10 | 0.08 | 0.001 | 0.506 |
| **85PC /15WFA** | OPI | 10.1 | 10.0 | 10.1 | - | 10.1 | 0.04 | 10.0 | 10.1 | 0.07 | 0.033 | 0.049 |
| **70PC /30WFA** | OPI | 10.2 | 10.2 | 10.2 | - | 10.2 | 0.01 | 10.2 | 10.2 | 0.02 | 0.881 | 0.004 |
| **90PC /10CGA** | OPI | 10.4 | 10.3 | 10.2 | 10.4 | 10.3 | 0.06 | 10.2 | 10.4 | 0.10 | 0.104 | 0.002 |
| **85PC /15CGA** | OPI | 10.1 | - | 10.0 | 10.1 | 10.1 | 0.04 | 10.0 | 10.2 | 0.07 | 0.041 | 0.030 |
| **70PC /30CGA** | OPI | 9.9 | 10.0 | 9.8 | - | 10.0 | 0.09 | 9.7 | 10.0 | 0.15 | 0.018 | 0.147 |

# APPENDIX E – SORPTIVITY INDEX

Table 31: 28 days: Sorptivity index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.50 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | WSI | - | 10.8 | 10.5 | 10.6 | 10.7 | 0.13 | 10.5 | 10.9 | 0.1993 | | |
| **90PC /10FA** | WSI | Invalid | 13.1 | 14.5 | 12.0 | 13.2 | 1.02 | 11.6 | 14.8 | 1.6237 | 0.0719 | |
| **85PC /15FA** | WSI | 12.4 | 12.4 | Invalid | - | 12.4 | 0.01 | 12.4 | 12.4 | 0.0080 | 0.0026 | |
| **70PC /30FA** | WSI | 11.7 | 11.6 | 11.0 | Invalid | 11.5 | 0.31 | 11.0 | 12 | 0.4994 | 0.0581 | |
| **90PC /10WFA** | WSI | 30.1 | - | 29.7 | 28.0 | 29.3 | 0.90 | 27.8 | 30.7 | 1.4331 | 0.0010 | 0.000083 |
| **85PC /15WFA** | WSI | 20.3 | - | 20.3 | 21.0 | 20.5 | 0.35 | 20 | 21.1 | 0.5532 | 0.0002 | 0.0009 |
| **70PC /30WFA** | WSI | 13.6 | 13.2 | 14.8 | - | 13.9 | 0.69 | 12.8 | 15.0 | 1.0986 | 0.0201 | 0.0241 |
| **90PC /10CGA** | WSI | 17.3 | 19.2 | Invalid | - | 18.3 | 0.95 | 16.8 | 19.8 | 1.5118 | 0.0771 | 0.0455 |
| **85PC /15CGA** | WSI | 11.0 | 11.0 | 11.8 | - | 11.3 | 0.36 | 10.7 | 11.9 | 0.5771 | 0.1271 | 0.0504 |
| **70PC /30CGA** | WSI | - | 20.1 | Invalid | 22.5 | 21.3 | 1.21 | 19.4 | 23.2 | 1.9239 | 0.0710 | 0.0698 |

Table 32: 56 days: Sorptivity index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.50 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | WSI | 8.3 | - | INV | 10.3 | 9.3 | 1.01 | 7.7 | 10.9 | 1.5990 | | |
| **90PC /10FA** | WSI | 8.7 | 8.7 | 9.7 | 9.3 | 9.1 | 0.41 | 8.4 | 9.8 | 0.6551 | 0.8848 | |
| **85PC /15FA** | WSI | 13.1 | 13.1 | 11.1 | 11.5 | 12.2 | 0.91 | 10.7 | 13.6 | 1.4417 | 0.1571 | |
| **70PC /30FA** | WSI | 7.6 | 9.7 | - | - | 8.7 | 1.07 | 7.0 | 10.4 | 1.6944 | 0.7133 | |
| **90PC /10WFA** | WSI | 24.6 | 23.6 | 24.8 | 24.0 | 24.3 | 0.49 | 23.5 | 25.1 | 0.7846 | 0.0297 | 0.000000 |
| **85PC /15WFA** | WSI | 11.8 | - | 14.2 | 15.5 | 13.8 | 1.55 | 11.4 | 16.3 | 2.4621 | 0.0598 | 0.2681 |
| **70PC /30WFA** | WSI | 13.6 | 13.3 | 14.5 | - | 13.8 | 0.51 | 13.0 | 14.6 | 0.8151 | 0.1070 | 0.1011 |
| **90PC /10CGA** | WSI | 12.5 | - | 12.9 | 13.5 | 13.0 | 0.38 | 12.4 | 13.6 | 0.6082 | 0.1493 | 0.0002 |
| **85PC /15CGA** | WSI | 11.8 | - | 11.3 | 11.9 | 11.7 | 0.25 | 11.3 | 12.1 | 0.3964 | 0.2465 | 0.4002 |
| **70PC /30CGA** | WSI | 11.2 | 11.6 | 11.8 | - | 11.6 | 0.25 | 11.2 | 12.0 | 0.3915 | 0.2562 | 0.2163 |

Table 33: 28 days: Sorptivity index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.60 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | WSI | 12.0 | 11.4 | 11.8 | - | 11.7 | 0.23 | 11.3 | 12.1 | 0.3723 | | |
| **90PC /10FA** | WSI | 12.5 | 13.1 | 13.2 | 12.6 | 12.9 | 0.30 | 12.4 | 13.3 | 0.4844 | 0.0052 | |
| **85PC /15FA** | WSI | 13.5 | 12.6 | 12.7 | 13.3 | 13.0 | 0.39 | 12.4 | 13.6 | 0.6208 | 0.0055 | |
| **70PC /30FA** | WSI | - | 11.0 | 11.8 | 11.2 | 11.3 | 0.36 | 10.7 | 11.9 | 0.5789 | 0.2676 | |
| **90PC /10WFA** | WSI | - | 24.9 | 24.5 | - | 24.7 | 0.19 | 24.4 | 25.0 | 0.3034 | 0.0001 | 0.000047 |
| **85PC /15WFA** | WSI | 21.7 | 22.4 | 20.8 | - | 21.6 | 0.67 | 20.6 | 22.7 | 1.0624 | 0.0008 | 0.0006 |
| **70PC /30WFA** | WSI | 15.7 | - | 15.6 | 15.3 | 15.6 | 0.16 | 15.3 | 15.8 | 0.2582 | 0.0001 | 0.0010 |
| **90PC /10CGA** | WSI | 15.7 | - | 14.4 | - | 15.1 | 0.66 | 14.0 | 16.1 | 1.0426 | 0.1049 | 0.1626 |
| **85PC /15CGA** | WSI | 16.9 | - | 16.1 | 16.8 | 16.6 | 0.36 | 16.0 | 17.2 | 0.5792 | 0.0003 | 0.000257 |
| **70PC /30CGA** | WSI | 14.8 | Invalid | 16.6 | 15.1 | 15.5 | 0.81 | 14.2 | 16.8 | 1.2878 | 0.0159 | 0.0086 |

Table 34: 56 days: Sorptivity index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.60 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | WSI | 12.6 | 12.0 | - | 13.2 | 12.6 | 0.47 | 11.8 | 13.3 | 0.7477 | | |
| **90PC /10FA** | WSI | - | 12.4 | 12.7 | - | 12.5 | 0.11 | 12.4 | 12.7 | 0.1750 | 0.9383 | |
| **85PC /15FA** | WSI | 10.2 | 11.7 | - | 10.9 | 11.0 | 0.61 | 10.0 | 11.9 | 0.9750 | 0.0451 | |
| **70PC /30FA** | WSI | - | 8.6 | 9.4 | 11.5 | 9.9 | 1.21 | 7.9 | 11.8 | 1.9222 | 0.0708 | |
| **90PC /10WFA** | WSI | 24.8 | - | 25.1 | 25.4 | 25.1 | 0.23 | 24.7 | 25.5 | 0.3702 | 0.0001 | 0.000009 |
| **85PC /15WFA** | WSI | 22.5 | 19.7 | 20.1 | - | 20.8 | 1.25 | 18.8 | 22.8 | 1.9863 | 0.0058 | 0.0024 |
| **70PC /30WFA** | WSI | - | 15.1 | 14.7 | 14.7 | 14.8 | 0.21 | 14.5 | 15.2 | 0.3413 | 0.0107 | 0.0254 |
| **90PC /10CGA** | WSI | 12.1 | - | - | 12.1 | 12.1 | 0.04 | 12.1 | 12.2 | 0.0557 | 0.2961 | 0.1318 |
| **85PC /15CGA** | WSI | 16.5 | 15.9 | 15.4 | 16.5 | 16.1 | 0.47 | 15.3 | 16.8 | 0.7555 | 0.0009 | 0.001028 |
| **70PC /30CGA** | WSI | 11.3 | 12.8 | INV | - | 12.1 | 0.77 | 10.8 | 13.3 | 1.2330 | 0.6326 | 0.1559 |

# APPENDIX F – CHLORIDE CONDUCTIVITY INDEX

Table 35: 28 days: Chloride conductivity index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.50 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | CCI | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.03 | 0.6 | 0.7 | 0.05 | | |
| **90PC /10FA** | CCI | - | 1.1 | 1.5 | 1.1 | 1.2 | 0.17 | 1.0 | 1.5 | 0.27 | 0.0444 | |
| **85PC /15FA** | CCI | - | - | 0.6 | 0.5 | 0.5 | 0.02 | 0.5 | 0.6 | 0.03 | 0.0110 | |
| **70PC /30FA** | CCI | 0.5 | - | 0.5 | 0.6 | 0.5 | 0.02 | 0.5 | 0.6 | 0.04 | 0.0011 | |
| **90PC /10WFA** | CCI | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.02 | 0.4 | 0.5 | 0.03 | 0.0001 | 0.0211 |
| **85PC /15WFA** | CCI | 0.6 | 0.5 | - | 0.5 | 0.5 | 0.05 | 0.4 | 0.6 | 0.07 | 0.0132 | 0.5806 |
| **70PC /30WFA** | CCI | 0.5 | 0.5 | 0.5 | 0.4 | 0.5 | 0.01 | 0.4 | 0.5 | 0.02 | 0.0003 | 0.0387 |
| **90PC /10CGA** | CCI | - | 0.6 | 0.8 | 0.6 | 0.6 | 0.08 | 0.5 | 0.8 | 0.13 | 0.4995 | 0.0247 |
| **85PC /15CGA** | CCI | 0.7 | - | 0.7 | 0.8 | 0.8 | 0.06 | 0.7 | 0.8 | 0.09 | 0.2831 | 0.0194 |
| **70PC /30CGA** | CCI | 0.5 | 0.5 | 0.6 | - | 0.5 | 0.03 | 0.5 | 0.6 | 0.04 | 0.0017 | 0.8725 |

Table 36: 56 days: Chloride conductivity index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.60 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | CCI | 0.5 | 0.5 | - | 0.6 | 0.6 | 0.07 | 0.5 | 0.7 | 0.11 | | |
| **90PC /10FA** | CCI | 0.7 | 0.7 | 0.7 | 0.9 | 0.8 | 0.07 | 0.6 | 0.9 | 0.10 | 0.0304 | |
| **85PC /15FA** | CCI | 0.8 | 0.5 | 0.4 | 0.8 | 0.6 | 0.16 | 0.4 | 0.9 | 0.25 | 0.5353 | |
| **70PC /30FA** | CCI | 0.8 | 0.7 | 0.7 | - | 0.7 | 0.03 | 0.7 | 0.8 | 0.05 | 0.0485 | |
| **90PC /10WFA** | CCI | 0.4 | 0.5 | 0.4 | 0.4 | 0.4 | 0.04 | 0.4 | 0.5 | 0.06 | 0.0814 | 0.0008 |
| **85PC /15WFA** | CCI | 0.6 | 0.5 | 0.6 | 0.4 | 0.5 | 0.06 | 0.4 | 0.6 | 0.10 | 0.6027 | 0.3582 |
| **70PC /30WFA** | CCI | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.03 | 0.4 | 0.5 | 0.05 | 0.1812 | 0.0008 |
| **90PC /10CGA** | CCI | - | 0.6 | 0.8 | 0.6 | 0.6 | 0.08 | 0.5 | 0.8 | 0.12 | 0.2798 | 0.2044 |
| **85PC /15CGA** | CCI | 0.7 | - | 0.7 | 0.8 | 0.7 | 0.03 | 0.7 | 0.8 | 0.04 | 0.0409 | 0.2804 |
| **70PC /30CGA** | CCI | - | 0.6 | 0.7 | 0.7 | 0.7 | 0.03 | 0.6 | 0.7 | 0.05 | 0.1361 | 0.1100 |

Table 37: 28 days: Chloride conductivity index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.50 water cement ratio

| **cement blends** | | **1** | **2** | **3** | **4** | **average** | **standard deviation** | **min** | **max** | **95% range** | **p-value 100% PC** | **p-value to FA** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | CCI | 0.8 | 0.9 | 0.8 | - | 0.8 | 0.03 | 0.8 | 0.9 | 0.04 | | |
| **90PC /10FA** | CCI | 1.2 | 1.4 | 1.4 | 1.3 | 1.3 | 0.08 | 1.2 | 1.5 | 0.13 | 0.0008 | |
| **85PC /15FA** | CCI | 0.8 | 0.8 | - | 0.9 | 0.8 | 0.01 | 0.8 | 0.9 | 0.01 | 0.9419 | |
| **70PC /30FA** | CCI | 0.8 | - | 0.8 | 0.8 | 0.8 | 0.01 | 0.8 | 0.8 | 0.02 | 0.1323 | |
| **90PC /10WFA** | CCI | 0.7 | 0.7 | 0.7 | - | 0.7 | 0.01 | 0.7 | 0.7 | 0.01 | 0.0220 | 0.0010 |
| **85PC /15WFA** | CCI | 0.8 | 0.9 | 0.9 | - | 0.8 | 0.03 | 0.8 | 0.9 | 0.05 | 0.7998 | 0.7985 |
| **70PC /30WFA** | CCI | 0.9 | - | 0.9 | 0.9 | 0.9 | 0.03 | 0.8 | 0.9 | 0.04 | 0.2447 | 0.0305 |
| **90PC /10CGA** | CCI | 0.5 | 0.5 | 0.4 | 0.4 | 0.5 | 0.04 | 0.4 | 0.5 | 0.06 | 0.000048 | 0.0001 |
| **85PC /15CGA** | CCI | - | - | 1.0 | 1.1 | 1.1 | 0.05 | 1.0 | 1.2 | 0.08 | 0.0903 | 0.1241 |
| **70PC /30CGA** | CCI | 1.1 | 1.3 | 1.4 | 1.1 | 1.2 | 0.13 | 1.0 | 1.4 | 0.21 | 0.0166 | 0.0135 |

Table 38: 56 days: Chloride conductivity index test results and statistical analysis for 100% PC, FA, WFA and CGA with 0.60 water cement ratio

| cement blends | | 1 | 2 | 3 | 4 | average | standard deviation | min | max | 95% range | p-value 100% PC | p-value to FA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **100PC** | CCI | 0.7 | 0.7 | 0.8 | 0.9 | 0.8 | 0.09 | 0.6 | 0.9 | 0.14 | | |
| **90PC /10FA** | CCI | 0.8 | 0.7 | 0.7 | 0.8 | 0.8 | 0.08 | 0.6 | 0.9 | 0.13 | 0.8384 | |
| **85PC /15FA** | CCI | 0.7 | 0.7 | 0.6 | 0.9 | 0.7 | 0.09 | 0.6 | 0.9 | 0.15 | 0.4316 | |
| **70PC /30FA** | CCI | 0.7 | 0.7 | - | 0.9 | 0.8 | 0.08 | 0.6 | 0.9 | 0.12 | 0.7836 | |
| **90PC /10WFA** | CCI | 0.6 | 0.6 | 0.7 | - | 0.7 | 0.05 | 0.6 | 0.7 | 0.07 | 0.0763 | 0.0881 |
| **85PC /15WFA** | CCI | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.01 | 0.7 | 0.8 | 0.02 | 0.6953 | 0.5088 |
| **70PC /30WFA** | CCI | 0.8 | 0.6 | 1.1 | 1.0 | 0.9 | 0.18 | 0.6 | 1.1 | 0.29 | 0.6206 | 0.5134 |
| **90PC /10CGA** | CCI | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.04 | 0.4 | 0.5 | 0.06 | 0.003489 | 0.0028 |
| **85PC /15CGA** | CCI | 0.9 | - | 1.0 | 1.0 | 1.0 | 0.04 | 0.9 | 1.0 | 0.07 | 0.0320 | 0.0126 |
| **70PC /30CGA** | CCI | 0.9 | - | 1.0 | 1.0 | 1.0 | 0.05 | 0.9 | 1.1 | 0.08 | 0.0273 | 0.0349 |

# APPENDIX G – DRYING SHRINKAGE STRAIN

Table 39: Drying shrinkage strain results and statistical analysis for 100% PC, FA, WFA and CGA with 0.50 water cement ratio

| | **0.5_100% PC** | **0.5_10% FA** | **0.5_15% FA** | **0.5_30% FA** | **0.5_10% CGA** | **0.5_15% CGA** | **0.5_30% CGA** | **0.5_10% WFA** | **0.5_15% WFA** | **0.5_30% WFA** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Test Age (day)** | **strain (ε)*10^-6** | | | | | | | | | |
| **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2** | 716 | 324 | 8 | 144 | 387 | 352 | 47 | 310 | 167 | 184 |
| **4** | 1098 | 496 | 195 | 258 | 612 | 492 | 89 | 550 | 292 | 367 |
| **6** | 1163 | 568 | 316 | 389 | 799 | 640 | 159 | 470 | 345 | 489 |
| **8** | 1163 | 558 | 336 | 477 | 876 | 613 | 246 | 624 | 421 | 722 |
| **10** | 1162 | 608 | 338 | 552 | 1013 | 713 | 408 | 685 | 440 | 862 |
| **12** | 1152 | 611 | 409 | 567 | 1091 | 744 | 555 | 987 | 522 | 963 |
| **14** | 1140 | 656 | 346 | 539 | 1190 | 808 | 686 | 1039 | 555 | 1044 |
| **16** | 1131 | 429 | 315 | 548 | 1280 | 881 | 769 | 1105 | 645 | 1116 |
| **18** | 1131 | 424 | 399 | 571 | 1345 | 940 | 770 | 1106 | 632 | 1183 |
| **20** | 1122 | 543 | 440 | 566 | 1622 | 1189 | 886 | 1170 | 696 | 1295 |
| **22** | 1135 | 711 | 547 | 575 | 1820 | 1365 | 963 | 1238 | 734 | 1454 |
| **24** | 1145 | 898 | 612 | 5663 | 2000 | 1513 | 1227 | 1316 | 837 | 1654 |
| **26** | 1200 | 1048 | 566 | 542 | 1975 | 1442 | 1374 | 1474 | 1062 | 1798 |
| **28** | 1335 | 1156 | 469 | 535 | 2027 | 1444 | 1674 | 1398 | 1208 | 1878 |
| **30** | 1395 | 1091 | 216 | 505 | 2101 | 1474 | 1993 | 1404 | 1314 | 1888 |
| **Average strain** | 1146 | 669 | 372 | 489 | 1342 | 974 | 790 | 992 | 658 | 1127 |
| **Std. dev.** | 138.93 | 249.84 | 139.20 | 123.58 | 537.95 | 382.94 | 562.68 | 360.95 | 320.67 | 526.16 |
| **n** | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 |
| **df** | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 |
| **t** | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 |
| **min** | 1069 | 530 | 295 | 420 | 1044 | 762 | 478 | 792 | 480 | 835 |
| **max** | 1223 | 807 | 450 | 557 | 1640 | 1186 | 1101 | 1192 | 836 | 1418 |
| **95% range** | 76.94 | 138.37 | 77.10 | 68.44 | 297.94 | 212.08 | 311.63 | 199.91 | 177.60 | 291.41 |
| **p-value (PC)** | | 0.0000 | 0.0000 | 0.0000 | 0.2051 | 0.1316 | 0.0354 | 0.1524 | 0.0000 | 0.8946 |
| **p-value (FA)** | | | | | 0.0004 | 0.0000 | 0.0690 | 0.0109 | 0.0065 | 0.0005 |

Table 40: Drying shrinkage strain results and statistical analysis for 100% PC, FA, WFA and CGA with 0.60 water cement ratio

| | **0.6_100% PC** | **0.6_10% FA** | **0.6_15% FA** | **0.6_30% FA** | **0.6_10% CGA** | **0.6_15% CGA** | **0.6_30% CGA** | **0.6_10% WFA** | **0.6_15% WFA** | **0.6_30% WFA** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Test Age (day)** | **strain (ε)*10^-6** | | | | | | | | | |
| **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2** | 547 | 349 | 90 | 116 | 198 | 133 | 89 | 234 | 241 | 248 |
| **4** | 941 | 465 | 183 | 209 | 318 | 224 | 272 | 402 | 378 | 355 |
| **6** | 1010 | 644 | 260 | 335 | 461 | 361 | 408 | 484 | 505 | 526 |
| **8** | 1183 | 657 | 400 | 498 | 545 | 487 | 688 | 561 | 556 | 550 |
| **10** | 1170 | 834 | 420 | 655 | 660 | 585 | 832 | 590 | 639 | 688 |
| **12** | 1156 | 852 | 366 | 789 | 716 | 593 | 980 | 6956 | 698 | 700 |
| **14** | 1121 | 898 | 438 | 930 | 778 | 603 | 947 | 747 | 756 | 766 |
| **16** | 1109 | 947 | 494 | 1097 | 870 | 662 | 893 | 838 | 838 | 838 |
| **18** | 1023 | 1033 | 537 | 1185 | 957 | 723 | 884 | 844 | 878 | 912 |
| **20** | 1026 | 1263 | 426 | 1203 | 1263 | 997 | 879 | 889 | 1055 | 1220 |
| **22** | 1038 | 1389 | 408 | 1226 | 1462 | 1068 | 951 | 917 | 1169 | 1421 |
| **24** | 1156 | 1497 | 455 | 1320 | 1629 | 1226 | 1035 | 975 | 1294 | 1614 |
| **26** | 1217 | 1408 | 461 | 1589 | 1584 | 1203 | 1087 | 1198 | 1367 | 1536 |
| **28** | 1357 | 1435 | 461 | 1806 | 1502 | 1337 | 1196 | 1363 | 1455 | 1547 |
| **30** | 1416 | 1448 | 451 | 1937 | 1329 | 1360 | 1361 | 1484 | 1531 | 1579 |
| **Average strain** | 1098 | 1008 | 390 | 993 | 951 | 771 | 834 | 815 | 891 | 967 |
| **Std. dev.** | 191.99 | 369.01 | 117.11 | 540.54 | 462.97 | 388.56 | 330.92 | 335.52 | 390.79 | 461.47 |
| **n** | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 |
| **df** | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 | 14.00 |
| **t** | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 | 2.145 |
| **min** | 992 | 804 | 325 | 693 | 695 | 556 | 650 | 629 | 674 | 711 |
| **max** | 1204 | 1212 | 455 | 1292 | 1208 | 986 | 1017 | 1001 | 1107 | 1222 |
| **95% range** | 106.33 | 204.37 | 64.86 | 299.37 | 256.41 | 215.20 | 183.27 | 185.82 | 216.43 | 255.58 |
| **p-value (PC)** | | 0.4272 | 0.0000 | 0.5013 | 0.2877 | 0.0103 | 0.0167 | 0.0118 | 0.0897 | 0.3377 |
| **p-value (FA)** | | | | | 0.7235 | 0.0028 | 0.3569 | 0.1583 | 0.0003 | 0.8915 |

# APPENDIX H – DATA SET ANALYSIS

The three or four test results per cement blend were used to provide the final result from each test. In order to assess the test results variability, an established statistical procedure for determining 'outliers' was applied based on mathematical statistics. An outlier is defined as an observation or data point which does not appear to fall within the expected distribution for a particular data set (Barnett & Lewis, 1994; Kanjee, 2015).

95% confidence interval was calculated using the t-distribution developed by W. S. Gosset (1908), the equation is;

$$(\bar{X} - t_{n-1}\frac{s}{\sqrt{n}} . \bar{X} + t_{n-1}\frac{s}{\sqrt{n}})$$

where

$\bar{X}$ = sample average
$n$ = size of random sample
s = sample standard deviation
t = T value obtained from the t-distribution tables, 95% confidence interval the corresponding t value; degrees of freedom (n-1)=2 was 4.303, (n-1)=3 was 3.182, (n-1)=14 was 2.145

Standard deviation calculation;

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n-1}}$$

where

$x_i$ = individual test results
$\bar{X}$ = sample average
$n$ = size of random sample

Using the equation above it was possible to determine a range which consisted of a low side and high side value for a 95% confidence interval. The confidence interval, allowed for data that fell out of the 95% confidence range to be identified as outliers. The outliers were then rejected and not included in the sample population.

# APPENDIX I – CHEMICAL COMPOSITION OF SUPPLEMENTARY CEMENTITIOUS MATERIAL

Table 41: Chemical composition analysis of FA, WFA and CGA

| Chemical compound (% by mass ignited basis) | Fly Ash (FA) | Weathered Fly Ash (WFA) | Coal Gasification Ash (CGA) | Δ = WFA-FA | WFA-FA (%) | Δ = CGA-FA | CGA-FA (%) |
|---|---|---|---|---|---|---|---|
| Loss on ignition | 1.76 | 11.76 | 6.95 | 10 | 568.18% | 5.19 | 294.89% |
| $SiO_2$ | 49.77 | 54.32 | 60.26 | 4.55 | 9.14% | 10.49 | 21.08% |
| $P_2O_5$ | 1.09 | 0.95 | 0.66 | -0.14 | -12.84% | -0.43 | -39.45% |
| $Al_2O_3$ | 31.88 | 26.69 | 21.52 | -5.19 | -16.28% | -10.36 | -32.50% |
| $Fe_2O_3$ | 2.8 | 5.23 | 3.97 | 2.43 | 86.79% | 1.17 | 41.79% |
| CaO | 7.83 | 9.8 | 7.6 | 1.97 | 25.16% | -0.23 | -2.94% |
| MgO | 2.01 | 2.78 | 1.7 | 0.77 | 38.31% | -0.31 | -15.42% |
| $K_2O$ | 1.07 | 1.02 | 1.13 | -0.05 | -4.67% | 0.06 | 5.61% |
| $TiO_2$ | 1.78 | 1.56 | 1.28 | -0.22 | -12.36% | -0.5 | -28.09% |
| $Na_2O$ | 0.3 | 1.33 | 0.37 | 1.03 | 343.33% | 0.07 | 23.33% |
| $Mn_2O_3$ | 0.04 | 0.08 | 0.03 | 0.04 | 100.00% | -0.01 | -25.00% |
| $SO_3$ | 0.02 | 0.03 | 0.01 | 0.01 | 50.00% | -0.01 | -50.00% |
| **Total** | **100.35** | **115.55** | **105.48** | | | | |
| **CaO** | **8%** | **8%** | **7%** | | | | |
| **$SiO_2$, $Al_20_3$, $Fe_2O_3$** | **84%** | **75%** | **81%** | | | | |

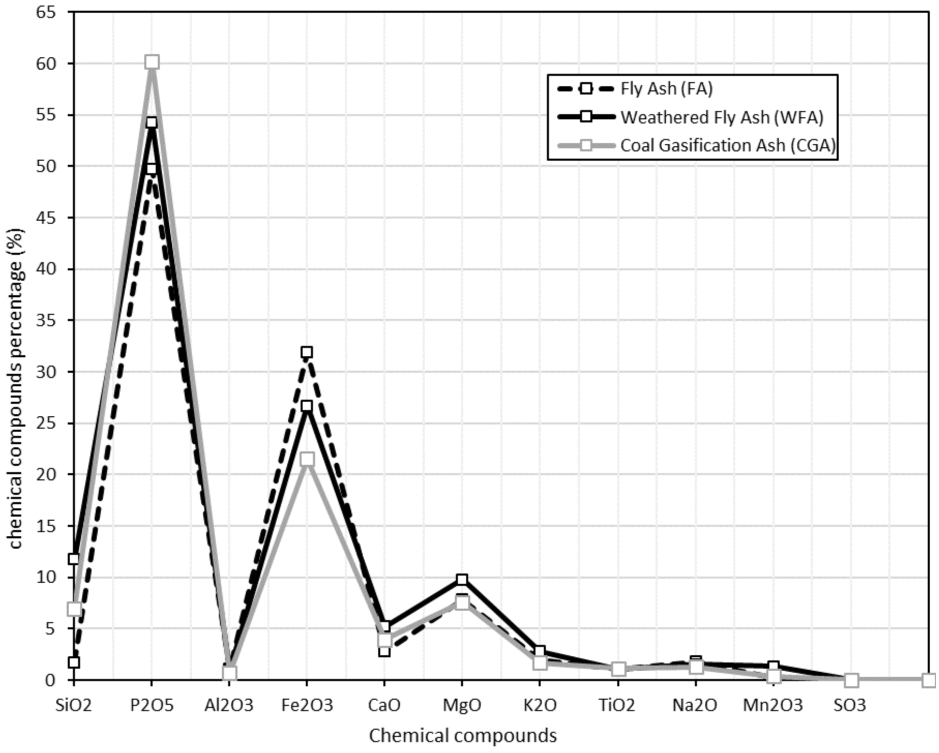

Figure 66: Chemical compounds of FA, WFA and CGA from XRF test