The effect of South African quaternary supplementary cementitious blends on corrosion behaviour of concrete reinforcement in chloride and Sulphate media

by

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DECLARATION

I declare that the above dissertation is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

It is being submitted for the degree of Magister Technologiae: Chemical to the University of South Africa. It has not been submitted for any degree or examination in any other University

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SIGNATURE	DATE

ABSTRACT

The aim of this study was to assess the strength, durability properties and corrosion resistance of concrete samples using supplementary cementitious blended materials. In this investigation, three supplementary concrete materials (SCMs) were used together with ordinary Portland Cement (OPC) to form cementitious blends at different proportions. The supplementary materials are silica fume (SF), ground granulated blast furnace slag (GGBS) and fly ash (FA). Sixteen (16) different proportions of the cementitious blends were produced. Tests carried out on concrete samples include slump test, compressive strength, oxygen permeability, sorptivity, porosity, chloride conductivity test, resistance to chloride and sulphate attack. The electrode potentials of tested samples were also observed using electrochemical measurements.

Concrete specimens prepared with 10%, 20%, 30%, 40%, up to 60% of blended cements replacement levels were evaluated for their compressive strength at, 7, 14, 28, 90 and 120 days while the specimens were evaluated for durability tests at 28, and 90 days respectively. The results were compared with ordinary Portland cement concrete without blended cement. Voltage, and temperature measurements were also carried out to understand the quality of concrete. The corrosion performance of steel in reinforced concrete was studied and evaluated by electrochemical half-cell potential technique in both sodium chloride, and magnesium sulphate solutions respectively. The reinforced concrete specimens with centrally embedded 12mm steel bar were exposed to chloride and sulphate solutions with the 0.5 M NaCl and $MgSO_4$ concentrations respectively. An impressed voltage technique was carried out to evaluate the corrosion resistance of the combination of quaternary cementitious blended cement, so as to get the combination with optimum performance. Improvement of strength, durability, and corrosion resistance properties of blended concrete samples are observed at different optimum percentages for binary, ternary and quaternary samples. The effect of cementitious blends is recognized in limiting the corrosion potential of the tested SCM concrete samples. Generally, the cementitious blends with limited quantity of SF to 10% have the potential to produce satisfactory concrete. These should however be used for low cost construction, where high quality concrete is not required.

Keywords: Compressive strength, Corrosion, Silica fume, Durability, Fly ash, Ground granulated blast furnace slag, Silica fume and Supplementary concrete materials.

STATEMENT OF ACHIEVEMENT

The following technical papers have been published from this investigation:

- **Akinwale A.E.,** Ikotun, B.D, Afolabi, A.S (2017) “Effect of South African quaternary extenders on early compressive strength”. Publication in the RTESE’17 Proceedings of the International Conference of Recent Trends in Environmental Science and Engineering, at Toronto, Canada from 23 – 25 August 2017. ISSN: 2561-1089 | ISBN: 978-1-927877-36-4

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DEDICATION

I dedicate this dissertation to God the Father, Son, and the Holy Spirit for the spiritual, mental, physical, and financial back up granted to me; more importantly strength, knowledge, and wisdom to accomplish this research work.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background and Motivation

The embedded reinforcement in concrete is usually sheltered from corrosion by a thick oxide layer formed on its exteriors because of the highly alkaline environment of the adjoining concrete. In spite of this protective mechanism, corrosion of the reinforcement remains one of the common durability challenges (Yoon 2006), as durability of reinforced concrete largely depends on the exposed environment conditions. One of the identified severe causes of this menace is the ingress of chloride, and sulphate ions to the reinforcement surface: because of the exposure to seawater in a marine environment, if reinforced concrete, which is a widely used construction material worldwide (Bertolini et al., 2004; Sideris and Sava 2005).

The concomitant risk of reinforcement corrosion is considered as the most serious degradation mechanism for reinforced concrete structure (Uelim and Bernhard, 2011). This has also been attributed to the level of exposure of reinforced concrete to environmental stress during the infrastructure lifespan, which affects the concrete or steel reinforcements (Ormellese et al. 2009). The effect of damage can be described in two ways. Firstly, it diminishes the cross-sectional area of the reinforcement; secondly, it induces tensile stress in concrete, which increases its volume, the outcome of which results in cracking and eventually leads to structural failure (Yoon et al. 2006).

The use of supplementary cementitious materials (SCMs) in concrete mixture has been studied extensively. Decades of field experience also validated laboratory work that air entrained concrete containing proportional mix of these SCMs improve resistance to scaling caused by the effect of deicing salts in a freeze thaw exposed conditions. Amir, (2016) reported the work of Bertolini et al (2004), which confirmed that SCMs decrease permeability of concrete through refinement of the pore structure and creation of secondary calcium silicate hydrate (C-S-H). The research also showed the findings of Holland (2012), which demonstrated that at low water-cement (w/c) ratio, there was a decrease of permeability, which resulted in a slower rate of carbonation than in plain Portland concrete.

Where adequate curing is in place, cementitious materials are found generally to reduce the permeability and absorption of concrete: thus, establishing correlation between the reduction of permeability of properly cured concrete and reduction in corrosion rates due to the effect of some supplementary cementing materials. This may in effect improve the sulphate resistance in the reinforced concrete structures.

Fly ash (FA) as one of the most widely used supplementary cementitious materials in concrete is a thermal plant by-product used in general building construction such as walls for residential buildings, pavements, high-rise towers, road construction and dams. It has potential capacity to obstruct voids and pores leading to a decrease of pore size, and to a smaller extent, effectively, for either chlorides or sulphate ions (Tae-Hyun 2007). Silica fume (SF) and metakaolin are also found to be effective in reducing the permeability and absorption of concrete (Barger 1997). Amir, et al. (2016) in their study on corrosion of steel in concrete structures reported the works of Papadakis (2000), where the replacement of cement with silica fume (SF) showed an increase in the carbonation depth at all ages. The outcome of Khurana et al. 2001 indicated that 30% Ordinary Portland Cement (OPC) replacement with FA can significantly improve fresh state properties, and the use of FA reduces the demand for cement, and fine fillers, which are required in high quantities in self-compacting concrete (SCC).

Gamage et al. (2014) observed that concrete containing class F Fly ashes mix are more resistance to sulphate attack than those mixes with class C Fly ashes. The classification of class F and class C can be categorized depending on chemical properties of the Fly ash. Class F FA is usually available in larger quantities, with less than 15% lime content compared to Class C FA with higher lime content often as high as 30%. FA is categorized as class C, with $SiO_2+Al_2O_3+Fe_2O_3$ making up at least 50 mass per cent while in pozzolanic FA, Class F containing $SiO_2+Al_2O_3+Fe_2O_3$ makes up more than 70 mass percent of the composition of FA (Landman AA 2003).

Class F FA also provides a solution to a wide range of summer concreting challenges and it is often recommended for use where concrete may be exposed to sulphate ions in ground water and soil, (Gamage et al. 2014). Start et al. (1996) further highlighted that class C FA shows a performance reduction in sulphate resistance against concrete mix with ground granulated blast-furnace slag (GGBS). This is considered beneficial in sulphate-exposed condition. However, this performance was not substantial due to the fact that the mixtures may not have been optimized for sulphate resistance when compared to concrete containing Portland cement in a long-term study. Earlier work by Muralidaran (2000) showed that FA might accelerate reinforcement corrosion caused by the presence of unburnt carbon and Sulphur. On the other hand, SF and metakaolin proved to be effective in permeability and absorption reduction.

Due to its wide variety of applications and composite nature, reinforced concrete is threatened by a number of exposed conditions, which include marine, industrial or other severe exposure. This exposure allows the ingress of external agents such as carbon dioxide, chloride or sulphate ions, which may eventually lead to the degradation and deterioration of the affected structures due to acid attack, alkali silica reactions, or freezing-thawing. (Boga and Topcu 2012).

The presence of chlorides as one of the external corrosive agents may manifest in the freshly mixed concrete when chloride-contaminated materials are used such as chloride in the cement or sea-dredged aggregates. Chlorides can also be found in the hardened concrete at a later stage when exposed to seawater or deicing salt such as calcium or sulphate chloride.

These media (calcium or sulphate chloride) can then lead to breakdown of steel passivity and thus present a risk of loss of rebar cross section and spalling of the concrete cover due to corrosion. This process will affect the durability performance of the affected structure. The existence of chloride or sulphate ion is therefore the basis of deterioration of concrete structural components exposed to groundwater and soils contaminated with sulphate salts or marine environments (Ogunbode et al. 2013).

1.2 Statement of the problem

Many studies focused on both physical, and mechanical properties of reinforced concrete with interest on the effect of fly ash blended cements and its improvements on both the strength and durability of the reinforced concrete. Detailed studies on the corrosion performance of quaternary cementitious blended cement concrete are rare especially in South Africa. Therefore, a detailed and realistic evaluation of the corrosion-resistance of quaternary cementitious blend is required. In addition, assessment of physical and mechanical properties of blended concrete is essential with a view to encourage the continuous usage of these available cementitious materials in South Africa.

1.3 Research Questions

The main research question for this study is:

> *"What is the effect of South African supplementary cementitious binders (Portland cement, ground granulated blast-furnace slag, fly-ash and silica fume) on corrosion behaviour of concrete reinforcement in chloride and sulphate media?"*

In order to answer this main research question, the following sub questions must be firstly addressed

- What are the causes of corrosion of reinforcement?
- How can these supplementary materials militate the corrosion of reinforcement in concrete?
- In what composition do the SCMs contribute to the general preservation of reinforcement in concrete?
- Which one of the two media under study is more passive or active?
- Will the percentage content of the supplementary materials influence the corrosive mechanism of the reinforcement in the two media?

1.4 Aim and Objectives of the study

In this study, the effect of South African supplementary cementitious materials (SCMs) in various percentage compositions with constant water/binder (W/B) ratio are investigated on the corrosion behaviour of reinforced concrete steel in the sodium chloride and sulphate media. The strength and durability index of the concrete samples are examined and the effect of interrelationships of various measured properties are discussed. The aim of the present investigation is a systematic study on the influence of FA, SF, GGBS and a combination of two or three of these cementitious blends on the corrosion resistance of steel in reinforced concrete by electrochemical techniques in 0.5M of both NaCl and $MgSO_4$ solution respectively. This aim is expected to be achieved through the following objectives:

- Determination of the chemical composition of Ordinary Portland Cement (OPC) and the South African supplementary cementitious binders under investigation.
- Determination of compressive strengths of concrete samples under investigation.
- Determining the effect of both sodium chloride and magnesium sulphate on the compressive strength of the concrete samples under investigation.
- Determination of the durability index (chloride conductivity test, oxygen permeability test, and water sorptivity test) of the concrete samples under investigation while monitoring the corrosion behaviour of the reinforcement.
- Investigation of the mechanism of corrosion of reinforcement in these media in the presence of these SCMs using half-cell potential test method.
- Study the effect of various compositions of SA supplementary cementitious binders (Portland cement, ground granulated blast-furnace slag, fly ash and silica fume) on the corrosion behaviour of the reinforcement immersed in 0.5M of NaCl, and $MgSO_4$ media.
- Recommendation on which supplementary cementitious binder will produce the best mix in terms of strength, durability and protection of reinforcement, when reinforced concrete is exposed to chloride or sulphate environment.

1.5 Contribution to knowledge

This study has provided more understanding on the effect of South African supplementary cementitious blends on corrosion behaviour of concrete reinforcement in chloride and sulphate media. The findings of this study will offer assistance in selecting suitable combination of supplementary cementitious materials for reinforced concrete structure that will be exposed to these media.

1.6 Scope and limitation of Study

This study focused primarily on South African cementitious materials and their influence on strength, durability and corrosion behaviour of concrete reinforcement in chloride and sulphate media using electrochemical measurements in line with the SANS 50197-1 standard requirements. This study was limited to measuring the effect of the South African binders, varying contents on the constant concentration of chloride and sulphate media, with constant W/B ratio, by measuring the electrochemical potentials of the reinforced concrete immersed in these two media at every five-day interval for a period of five months.

1.7 Organization of the dissertation

Chapter 1 presents the introduction of the study

Chapter 2 presents the literature review on previous and relevant works done relating to the study.

Chapter 3 presents the methodology adopted in achieving the objectives set out in this work. It reports the various experiments performed in line with established standards for both materials and procedure used during the study. This include the sample preparation, casting of reinforced concrete, various tests such as compressive strength, durability index, water contents, scanning electron microscopy, and electrochemical measurements of the reinforcements.

Chapter 4 presents the results of the experiments and analysis of results obtained, detailed explanation and discussions are also in this chapter. The results obtained were compared to those obtained by various researchers who have worked on areas similar to the current study.

Chapter 5 presents the conclusion and recommendation for further studies not covered in this investigation.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

Reinforced concrete is a composite of concrete and reinforcement that is widely used as a construction material. This complementary material according to Oyenuga et al. (2004) comprises of concrete and steel with their attributed crushing strength, fire resistance, and tension properties. Though this composite material provides no tensile strength but perform favourably in shear and compression. However, steel which is incorporated within the concrete has high tensile stress resistance but has low resistance to fire due to rapid loss of strength when subjected to high temperature. The amalgamation of inherent properties results in good tensile, compressive strength, durability, and good resistance to fire and shear, Oyenuga et al. 2004 concluded. Due to its technical, economic and ecological advantages, its dense nature at hardened stage has excellent strength, and durability properties (Pradhan et al. 2014), which made it to perform considerably well in construction of structures located in aggressive environmental conditions varying from mild to severe. Despite the increase request for this material in severe environments, the concern towards life-span reliability under harsh condition increases. Though, these materials produce excellent service under such environmental conditions (ÌIker and Ahmet, 2010), the performance of reinforced concrete which is directly linked to chloride-induced corrosion, water-to-cement ratio, presence of surface cracks, exposed humidity, temperature, and the thickness of cover is been undermined (Farahani et al. 2015).

As reported by Pradhan, et al. 2014, the exposure conditions of concrete is classified into three categories: which are mild, severe and extreme environments. These conditions include among others concrete surfaces exposed to weather, severe rain, and structural members exposed to tidal zone respectively.

Therefore, because of the exposure conditions of reinforced concrete, it is prone to deterioration. In order to meet the serviceability limit state (SLS) requirements of reinforced concrete structures, any structural member must be serviceable and perform its intended function throughout its working life under service loads. This SLS of reinforced concrete structures (RC) is primarily controlled due to damaging effect resulting from serviceability limit and other deterioration processes; which are active throughout the structure's designed life.

Apart from structural failure resulting from excessive service loads among others, the significant causes of deterioration of reinforced concrete structures resulting from chloride penetration into the reinforced concrete can be traced to three sources, which are considered the primary cause of reinforcement corrosion. Firstly, at the initial preparation of fresh concrete, resulting from the chloride contaminated aggregates and mixing water. (Pradhan, 2014). Secondly, into the hardened concrete through the application of deicing salts in bridge decks, parking structures and from seawater in marine structures; and thirdly, from soil and ground water containing chloride salts (Darquennes et al. 2016). This is directly linked to corrosion of reinforced concrete partly due to carbonation or chloride-induced depasivation of steel reinforcement, (Basheer, 1996). Ha-Wong Song et al 2006, reported this same position. The research indicated that corrosive effect resulted in cracking, and eventually leading to concrete spalling; leading to the reduction of the bond strength (Cheng et al 2005). The cracks may accelerate the ingress of detrimental ions and enhance concrete deterioration resulting in further cracking. (Arya et al. 1996 ; Ballim et al. 2003; Mohammed et al. 2001). According to Vidal et al. 2004, the impact of such cracks development on the corrosion of reinforced concrete structures is significant. Mehta (1997) concluded that to enhance sustainable production of blended cements in the construction industry, supplementary cementitious materials, which are product of thermal power plants, must be of proportional mix: This is consistent with Darquennes et al. 2016.

Supplementary cementitious materials (SCMs) can be categorized into two types: natural and artificial. The latter are siliceous by-products such as fly ash and metallurgical slags while the former are natural pozzolan such as volcanic tuffs (Papadakis and Tsimas 2002). In the study of Papadakis et al., 2002, it was observed that fly ash sample exhibited considerably lower chloride permeability as compared to the control sample. The increase FA content in the concrete volume produced a reduction in chloride permeability. Interestingly, it was noted that there is a resemblance in the results for natural pozzolan (milos earth and diatomaceous earth) used. However, the permeability is higher as compared with the fly ash specimen and when these materials replaced cement in some cases; higher chloride permeability than the control samples is observed. The above SCMs durability enhancement characteristics was also corroborated by the work of Darquennes et al. (2016); who determined the effect of self-healing property of ground granulated blast furnace slag cementitious materials on chloride resistance using chloride migration. The test confirmed self-healing reduces chloride penetration, and improves structural durability, predominantly for samples containing blast furnace slag. Although crack width is the main parameter affecting the chloride migration and not the material characteristics. Darquennes et al. (2016) observed that samples containing blast-furnace slag are more severed by the presence of a crack thus reducing significantly advantages of using ground granulated blast-furnace slag mixtures to limit chloride penetration. However, cementitious materials containing GGBS possess self-healing capacity that are sufficient enough to reduce crack dimensions and prevent penetration of aggressive agents. In Darquennes et al. (2016) work, chloride migration test was found to be an adequate technique to control the self-healing process as well as determining the effect of curing period and mixing proportionality on its kinetics.

2.2 Reinforced Concrete Corrosion Mechanism

Otieno et al. 2010 defined corrosion as the spalling of the concrete resulting in material wastage that can be found on the surface of the concrete: this occurs when metals are exposed to reactive environments. This process is electrochemical in nature where iron enters into solution at the anode and the oxidizing agent is reduced at the cathode, resulting in the movement of electrons between the anodic and cathodic sites on the steel. This damage effect, otherwise known as corrosion, occurs due to the inherent instability nature of metals in the metallic form and its susceptibility to corrode when exposed to the atmosphere.

Steel bar inside concrete is secure against corrosion through chemical, and physical mechanisms. However, the chemical fortification can be enhanced depending on the pH (usually between 12.5 -13.5) of the concrete interstitial solution which is responsible for passivation of the reinforcing steel, (Kandaker and Hossain 2004, Dinakar et al. 2007). Within the alkaline spectrum, a thin passivating protective film formed on the steel surface can be changed if the configuration of this protective film is altered when the pH is reduced. Alkalinity could reduce from 12.5 to around 9 due to penetration of atmospheric CO_2 into the concrete. Dinakar et al. (2007) further reported that the addition of FA or slag as SCMs may cause a further reduction in pH due to pozzolanic reaction. It is also reported that carbonation, which is a product of reaction between the carbon dioxide (CO_2) in the atmosphere and calcium hydroxide ($Ca(OH)_2$) in the concrete may further lower the pH value below the corrosion threshold limit of 9.5, thereby resulting in depassivation of steel; and ultimately lead to corrosion. The embedded steel reinforcement, based on pH of the concrete (electrolyte) in the presence of aggressive ions could produce the anodic and cathodic reactions in equation 2.1 to 2.6 (Hansson, 2016).

$$3Fe + 4H_2O \longrightarrow Fe_3O_4 + 8H^+ + 8e^- \quad \text{.....................................} 2.1$$

$$2Fe + 3H_2O \longrightarrow Fe_2O_3 + 6H^+ + 6e^- \quad \text{.....................................} 2.2$$

$$Fe + 2H_2O \longrightarrow HFeO_2^- + 3H^+ + 2e^- \quad \text{....................................} 2.3$$

$$Fe \longrightarrow Fe^{2+} + 2e- \quad \text{...} 2.4$$

$$2H_2O + O_2 + 4e^- \longrightarrow 4OH^- \quad \text{……………………..............................} 2.5$$

$$2H_2O + 2e^- \longrightarrow 2H^+ + 2OH^- \quad \text{...} 2.6$$

Research indicated that the high alkaline medium provided by the cement matrix in concrete allows the steel reinforcement to be in a passive state, and the formation of iron oxide on the steel surface may significantly reduce the corrosion rate (ÌIker and Ahmet, 2010). ÌIker and Ahmet, 2010 position is consistent with Otieno, et al. 2010 who indicated that the embedded concrete reinforcement is protected by both physical barriers of the concrete cover that reduces the amount of oxygen, moisture, carbon dioxide and likelihood of chlorides, which may activate corrosion as well as the high alkalinity of the cement matrix (pH>12.5). The protection resulted from the high alkalinity of the cement matrix due to the presence of sodium hydroxide (NaOH) and potassium hydroxide (KOH) as a result of dominant effect of alkalis in the cement, i.e. sodium oxide (NaOH) and potassium oxide in a saturated calcium hydroxide ($Ca(OH)_2$ solution. The research further affirmed that lack of penetrability of corrosive species such as carbon dioxide and chlorides into the concrete during its life span may reduce concrete reinforcement passivation during its entire service life due to the alkalinity of concrete pore solution, which may result in negligible corrosion rate. This is due to high pH suppressing steel corrosion through encouragement of very thin (1-10 nm) passive ferric oxide film (maghenite, y - Fe_2O_3) on the steel surface.

This composite material (reinforced concrete), also provides physical protection by inhibiting the access of aggressive agents, which depends on the porosity of the hardened cement paste at the early age. Often, the ingress of chloride ions leading to film depassivation often resulted to corrosion (Tuuti, 1982). Addition of SCMs such as fly ash, slag, and silica fume as pozzolans to concrete has therefore become the norm in recent years to improve the mechanical properties, bond strength, freeze-thaw durability, impermeability, corrosion control and workability of the concrete (Hou and Chung 2000). Previous studies have been carried out on the use of volcanic ash (VA), volcanic pumice powder (VPP), FA, pulverized-fuel ash (PFA), blast furnace slag, rice husk ash, to mention but a few as cement replacement material (Bilodeau and Malhotra 2000). However, FA is regarded as the most commonly used worldwide (Boga and Topcu 2012). This is because its presence in concrete increases the porosity of the hardened cement paste at early age although the pore size is reduced and often results in less permeable paste (Chindaprasirt et al. 2007).

Reinforcement corrosion may be initiated due to deterioration of the affected structures. Otieno et al. 2010 in his study itemized three stages of reinforced concrete degradation process, which include (i) initiation, (ii) propagation and (iii) an acceleration period. Little deterioration takes place during the initiation period, but enormous cracking result during the propagation phase. The rate of corrosion increases during the acceleration period, due to easy access of oxygen, water, and presence of aggressive agents through cracks, and spalling of the reinforced concrete. This development affects the penetrability and reliability of concrete cover in controlling the rate of corrosion as the boundary between the propagation and acceleration phase may be dependent on the tensile strength of the concrete. It has been reported by Rasheeduzzafar et al. (1991) that chlorides is an effective destroyer of ferric oxide film that protects the steel from corrosion. The destructive level of the ferric oxide will depend on the level of chloride concentration.

The production demand for reinforced concrete structure in harsh environment has been on the increase overtime (Pradhan, et al. 2014). This has prompted an increase in concern towards serviceability requirements of the reinforced concrete structure exposed to these harsh environmental conditions. They are categorized into mild and severe with different exposure conditions such as concrete surface exposed to aggressive conditions, severe rain, alternating wetting and drying or occasional freezing or severe condensation, usually peculiar to coastal environments (Pradhan, et al. 2014). These conditions could among others include extreme environmental exposure of structural members in tidal zones, and direct contact with aggressive chemicals such as radioactive waste. (Monteiro et al. 2003) and concrete exposed to chlorides used in industrial applications (Bertolini et al. 2004).

Reinforced concrete is intrinsically a durable composite material (Kobayashi et al. 2010). Often, when the passive film on the steel surface is destroyed by the chloride of marine salt, the steel corrodes, and the reinforcing concrete members deteriorates over time, which causes the volume of corrosion products to be larger several times than that of sound steel (Kobayashi et al., 2010). Eventually induces a high expansive pressure on the rebar corrosion, which leads to formation of cracks in the cover concrete. The presence of cracks therefore accelerates the ingress of detrimental ions leading to concrete degradation and result in further cracking (Cheng, et al. 2005). Various authors (Arya 1996, Ballim et al. 2003, Mohammed et al. 2001, Vidal et al. 2004, Ram et al. 1998) described the impact of cracks on the corrosion of reinforced concrete members as severe in nature.

It has been reported in the literature, that chloride can be added intentionally as cement hydration accelerating admixture, or through sea water in marine, and offshore exposed structures. Also, chloride salts can be added into the concrete through mix ingredients such as unwashed chloride contaminated crushed limestone coarse aggregates and coastal sands used as fine aggregates especially around the Middle East and other parts of the world. Where desalinated or potable water is scarce, concrete is more often mixed and commonly cured with brackish service water (non-desalinated tap water). This allows sufficient amount of chlorides penetration during the mixing of the concrete either through the aggregates or curing medium.

Chlorides also have its way into the concrete as secondary or external chlorides from outside sources during the service life of the hardened structures. According to Rasheeduzzafar et al. (1991), the level of free chloride concentration in the pore solution can be raised if the chloride content of the cement paste is increased. The pore solution data show the effect of C_3A on chloride binding in conjunction with the data developed in two pore solutions studies by Page and Vennesland (1983) and Diamond (1986) on 7.37 and 9.1% C_3A plain cements respectively. The compositions of the four cements are shown in Table 2.1 below:

Table: 2.1: Composition of Portland cement

Cement No.	Oxide Composition (% by weight)									Potential compound composition (% by weight)			
	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Na_2O	K_2O	Eqv.Na_2O	LOI	C_3S	C_2S	C_3A	C_4AF
1	64.20	21.90	3.98	4.80	1.71	-	-	0.58	1.10	54.30	21.80	2.43	14.61
2*	63.92	20.76	4.73	2.40	3.00	0.41	1.18	1.19	0.71	57.17	16.53	7.37	9.27
3*	64.50	20.90	5.00	3.05	3.21	0.10	0.69	0.55	2.15	57.80	16.50	9.10	7.40
4	64.70	19.92	6.54	2.09	2.61	0.28	0.56	0.65	1.10	54.50	16.00	14.00	6.50

*Page et al 1983 ; Diamond 1986 Source : Rasheeduzzafar et al. 1991

This destructive action facilitates chloride penetration into the cover concrete thus accelerating the corrosion progress. At an early stage of reinforced concrete, it is said that corrosion on the rebar increases the bond strength due to expansive pressure. However, once cracks are formed in the cover concrete, the bond strength is reduced which thus reduces the integrity between the rebar and the concrete (Kobayashi et al., 2010).

Structural durability as an important design and construction criteria must be assessed for every structural element designed for intended design loads and service life span especially for RC structures located in an aggressive environment. This important design criteria becomes imperative, since its structural durability can easily be compromised if reduced by physical, chemical and mechanical processes that trigger reinforcement's corrosion.

It is important, to study the effect of more than two of these SCMs produced locally in South Africa. Though, study have shown that a combination of more than two or more SCMs blended with OPC may extensively improve concrete performance exposed to chlorides. Amir et al. 2016 reported that the inclusion of SCMs can reduce the diffusion coefficient and permeability of concrete considerably. However, the type of blended cements used depends on the mixing proportion, application, and the age of exposure.

2.3 Ways of mitigating corrosion in reinforced concrete

To mitigate corrosion of steel reinforcement in concrete structures with the application of cementitious materials, it is expedient to understand the transport mechanism of corrosion and that of cementitious blends as a key factor to mitigate corrosion. Corrosion, leaching or carbonation are all related to the ease with which a fluid or ion can move through the concrete microstructure (Otieno, et al. 2010). However, the steel bar can be adequately protected against corrosion in a concrete that is properly compacted and cured under favourable atmospheric conditions (Dehghantan, et al. 1982).

It becomes apparent that design approach where durability and structural requirements are required should consider design procedure that will guarantee the performance of the structure from durability perspective (Litzner, H.U and Becker, A. 1999). The movement of potentially aggressive species within the composite material (RC) is primarily influenced by the penetrability of the concrete, which is defined as the degree to which a material allows the transport of matter either in form of gases or liquids. This embraces the concept of permeability, sorption, diffusion, and is quantifiable in terms of transport parameters (Otieno, et al. 2010).

This movement of damaging species occurs through a distinct process of capillary action, fluid flow under pressure, flow under a concentration gradient and movement due to applied electric field. All these are characterized by the materials properties of sorptivity, permeability, diffusivity and conduction respectively (Otieno et al. 2010). He further noted that there are more than one single transport mechanism operating at a given time either in parallel or in different sections along the flow path and it might not be ideal in selecting a single transport mechanism while propagating a remedial action against the cause effect of corrosion. He therefore advocated for an in-depth understanding of the individual's mechanisms and further studies on transport process to obtain a model for predicting simultaneous movement of the media (chloride, sulphate, oxygen, carbon dioxide, and moisture) and the deposition of ions be vigorously pursued using field test approach method that can assess combined transport mechanism.

Assessment of transport mechanism in dealing with the mitigating cause effect of corrosion will not be completed without examining the transport properties of cracked concrete as well as effect of concrete aging on transport mechanism since the presence of cracks may significantly modify or influence transport properties of concrete. In addition, the awareness of transport properties of cracked concrete is vital for durability prediction since the deteriorating mechanism (freeze and thaw, leaching and corrosion) depend on the flow of aggressive agents through the cracked concrete.

Substantial attention has been given to crack width from design perspective due to different exposure conditions. Clifton, 1993 and Blunt, et al. 2014 postulated that limiting the allowable crack width could reduce the rate of corrosion. Therefore, reinforced concrete structure intended for a particular corrosive environment requires a prudent approach with the aim of enhancing the cracking resistance of the concrete matrix to prevent the ingress of chlorides. Blunt, et al. (2014) agreed that alternative remedy for an enhanced degree of crack control could be the application of fibre reinforcement.

2.4 General behaviour of blended cement concrete

Technological advancement within the cement production process has brought about the use of mineral admixtures such as FA, SF and GGBS in the production of high-performance concrete which has proven to be effective in protecting corrosion of reinforcing steel.

The usage of these cementitious blends became striking due to its easiness, and relative low cost, (Boga et al. 2012). When FA is used as a fine granulates, it has potential of obstructing voids and pores upon hydration. The combination of FA particles with calcium hydroxide ($Ca(OH)_2$) produces hydration product that brings about decrease in concrete porosity. Consequently, FA contributes to a smaller effective diffusivity for either chlorides or other species, which finally leads to an increase of the concrete resistivity (Choi, 2006). Boga et al. 2012, conducted a study with the aim of producing a durable concrete against corrosion with low permeability of chloride ion using CEM I 42.5, with varying FA % composition (0, 15, 30, and 45) replacement. The specimens were subjected to two different curing conditions (air, and water) for both 28 and 56 days respectively to determine the effect of curing time on physical and mechanical properties of concrete with FA. The results show that mechanical properties of concrete and corrosion performance of reinforcement within the concrete changed in various degrees depending on the curing type, FA % used and duration of curing applied to concrete specimens. In addition, it was concluded that concrete sample with FA at 15% ratio replacement is beneficial to concrete production as the durability of reinforcement within concrete against corrosion was increased significantly due to application of curing method for 56 days.

Cheng, et al. (2005) reported general behaviour of blended cements with GGBS, which performed better than Portland cement when used in concrete. This position is consistent with Vikas, et al. 2015, who reported various advantages of cementitious materials in reducing corrosion of reinforced concretes in hot climates. In fact, he against using OPC alone in both marine and coastal structures.

Tests conducted by Arya, et al. 1995 and Glass, et al. 2000, on mortars containing GGBS indicated prominent reduction in permeability and penetration of chlorides ions in GGBS specimens. This beneficial effect resulted from the modification to cementitious paste microstructure with more capillary pores filled with low-density C-S-H gel than ordinary Portland cement paste. The above-mentioned authors also confirmed that the addition of GGBS can influence the electromechanical response of pore solutions in cement system; this position is consistent with the findings of Daude, et al. (1983) when he observed that GGBS can be effective in reducing the pore size and reduced the cumulative pore volume considerably Choi et al. (2005).

The effect of GGBS on hydrated cement structure, permeability, and chloride ion penetration confirmed that higher GGBS percentage replacement produced denser structure and may prevent concrete from water penetration. Daube, et al. (1983) suggested that chloride-ion diffusion coefficient of concrete with 60% slag replacement with 0.5 water/cementitious ratios is ten times smaller than concrete with OPC. However, Cheng, et al. (2005) reported that GGBS concrete produced higher compressive strength than OPC after pozzolanic reaction is completed. He further alluded to the fact that higher GGBS replacement % has higher ultimate strength within the range of his study, which corresponded with previous study carried out by Sivasunaram, et al. (1992), good strength developments of concretes containing between 50 to 75% of GGBS by mass of cementitious materials (300-420 kg/m^3) was observed.

Thomas, (1996) reported the reduction in chloride threshold with an increasing FA content. Furthermore, FA concrete exhibited an increased resistance to chloride penetration and higher electrical resistance Choi, et al. 2006, and Tae-Hyun et al. 2007. In agreement with the work of above mentioned authors, Renjaswamy, et al. 1981 and 1996, Mangat, et al. 1991, and Muralidharan et al. (2000) studies reported that FA could accelerate the corrosion of steel in concrete. Therefore, to produce quality FA with stable mechanical properties, it is imperative for the power plants operator to enhance quality control measures.

Also, extensive studies carried out by Salta, et al. 1994, Ampadu, et al. 1999, Bai, et al. 2000, Bahera, et al. 2000 on property improvement of FA blended cements confirmed that both the physical and mechanical properties of FA cement compared favourably with OPC.

Angst et al. (2009) reviewed literatures on chloride content in FA reinforced concrete and came with a conclusion that the critical chloride decreased with increasing amount of FA replacement. He stated that FA improves the chloride binding capacity of the binder, which could be attributed to higher proportions of active alumina often present in FA (Arya, et al. 1990; Dhir, et al. 1999), and better physical adsorption of chloride as the result of more gel produced during the hydration process (Kayyali, et al. 1995). Nevertheless, interestingly, the use of FA was found to lower the pH of the pore gel liquid (Byfors, 1987; Diamond, 1981).

2.5 Effect of blended cement concrete on reinforcement corrosion

Boga et al. (2012) confirmed the generally accepted notion that inclusion of FA improves concrete protection against chloride-induced corrosion of steel reinforcement in blended concrete. This is possible through the reduction of its permeability, and diffusivity, particularly to chloride ion transportation thus increasing the resistivity of the concrete. Vikas et al. 2015 is of the view that ternary cementitious blends (Ordinary Portland Cement, Fly Ash, and Alcofine) offer significant advantages over binary blends. He concluded that in terms of durability, such blends are vastly superior to OPC mortar. This material has distinct characteristics of enhancing concrete performance both in fresh and hardened stages.

Considering the rapid chloride permeability test conducted by Boga, et al. (2012) on concrete specimens subjected to two different curing durations of 28, and 56 days exposed to two different conditions (air, and water), it was found that chloride permeability of all samples without FA addition are high. Chloride permeability of concrete specimens cured in water for both 28 and 56 days were very low when FA is used at 30% and 45% replacement of cement.

But this chloride permeability level increased to moderate level when FA was used at the 30 and 45% ratios with the concrete samples cured in air for 28 days compared to series at which FA was used at 15% ratios.

The devastating effect of corrosion on reinforcing bar has tremendous influence on the strength, durability and serviceability limit state of the affected structural members. The loss of bond strength, and stiffness as a result of corrosion, may further cause extra deflection to the affected concrete structure. Cheng, et al. (2005) in their study confirmed that GGBS concrete beam has a higher stiffness ratio than the reference concrete beam. In their final analysis, according to Cheng, et al., (2005), no adverse effect on corrosion resistance was observed with the reduction of pH value that resulted from the addition of GGBS. They further added that the cracks width has a major effect on the corrosion rate of reinforcing steel in concrete. The GGBS concrete exhibits lower corrosion rate or higher corrosion resistance.

Their investigation shows that corrosion resistance increased with decreasing water-to-binder ratios; in addition, FA usage in concrete has advantage on corrosion resistance of steel due to the decreased permeability of chloride ions. More importantly, the use of FA led to increase the charge transfer, which has a direct correlation with lower corrosion rate. Open-circuit potential evolutions of concrete specimens with FA were more constant than those without FA. The works of Vikas, et al. 2015 confirmed the blended cements particularly those made with SF and GGBS are better in sodium sulphate environment.

2.6 Electrochemical techniques

A review of literatures provides detailed information about different electrochemical techniques for the corrosion measurements of reinforcing bar such as weight loss, half-cell potential measurements, impressed voltage method, impressed current method and potentiodynamic polarization method. Each technique provides some information about the condition of the steel bar (passive or active), or the corrosivity of the environment being evaluated. Electrochemical polarization technique is used as a valid indicator for measuring corrosion rate and an accelerated method for determining whether given medium is corrosive or inhibitive.

Half-cell potential of steel in concrete has been found to be a fast indicator of corrosion activity (Morsy, et al. 1995). It is simple, inexpensive and virtually non-destructive (Nakamura et al. 2008). This technique can be used to estimate the corrosion risk of steel in the absence of surface corrosion signs which is a significant advantage for inspecting existing concrete structures. This technique is also used as a means of interpreting corrosion phenomenon simply because it provides information on whether the anodic or cathodic process or both are controlling factors of corrosion (Morsy, S.M. et al. 1995). Its usefulness provides information on film breakdown and repair, but this method cannot be used to predict or measure corrosion rate. Therefore, for a reliable evaluation of the actual corrosion state, there is a need to use corrosion rate measurements together with half-cell potential (Morsy, et al. 1995).

2.7 Salinity effect on compressive strength of reinforced concrete

The effect of salt water either as a mix or curing medium on the compressive strength of reinforced concrete have been studied by Amin et al. 2008, Abalaka et al. 2011, Yang et al. 2012, Akinsola et al. 2012, Hassan, et al. 2013, Tiwari et al. 2014 extensively. Tiwari et al. 2014 reported a marginal increase in the strength of concrete samples cast and cured in salt water as compared to those of samples cast and cured in water at all ages of curing.

The design grade of M-30 with 1:1.8:3.31 by weight of concrete with 0.45 water-cement ratio was cast, the results of the concrete samples mix with fresh and cured with fresh water were compared with concrete samples cast and cured with salt water. The concrete samples subjected to water curing for 7, 14 and 28 days have the average compressive strength varies from 27.12 – 39.12 MPa while the salt-water mixing and curing have compressive strength ranges from 28.45-41.34 MPa respectively. This is in contrast to Akinsola et al. 2012 findings which revealed that concrete samples that were cast and cured using fresh water gained appreciable compressive strength as against samples that were cast and cured using ocean water. Although both samples were cured for 150 days period. The 14th day compressive strength results revealed 17.48 MPa for fresh water sample as against 12.10 MPa and 12.55 MPa recorded for both ocean and lagoon water samples.

Abalaka et al. 2011 studied effects of sodium chloride solutions as curing medium at concentrations of 5%, and 10% on compressive strength. Concrete samples containing 5% RHA in NaCl solutions produced early compressive strength increase at 3 and 7 days over control samples but concrete samples containing 5% RHA cured in NaCl solutions recorded higher strength loss compared to control samples at 28 days. His findings is consistent with the early study conducted by Henry et al. 1964 on sodium chloride as a mixing medium. Henry et al 1964 reported that increase in compressive strength can be obtained in the environment of NaCl solution at concentration of 25 gm per 1kg of solution without causing the corrosion of mild steel.

However, NaCl has been reported to cause set acceleration in some cements and retarding effects in others (Mattus et al. 1994). It is reported by Amin et al. 2008 that sulphate ions in soils, ground water and seawater may cause cracking due to factors such as cement type, sulphate cation type, sulphate concentration and the period of exposure.

The degradation effect of the aforementioned factors need to be repaired, or in most severe cases, need to be reconstructed. (Neville et al. 1995, Gollop et al. 1996, Marchand et al. 2002, Santhanam et al. 2002, Torres, et al. 2003, and Hekal et al. 2004. From the literature review, there is an indication that blended cementitious materials can inhibit steel corrosion in concrete. Hence, the current study will look at the effect of South African quaternary supplementary cementitious materials on corrosion behaviour of concrete strength, durability and concrete reinforcement in chloride and sulphate media.

CHAPTER THREE

3.0 MATERIALS AND EXPERIMENTAL METHODS

3.1 Introduction

The experimental procedure was carried out in two phases. The first phase dealt with the work on fresh and hardened concrete, which included the following materials properties. Workability, compressive strength, permeability, sorptivity, and chloride conductivity tests. The second phase dealt with the corrosion tests, which included voltage, pH, and temperature measurements.

3.2 Materials

For casting concrete specimens, Ordinary Portland cement (OPC) with class 52.5N conforming to South African Standards SANS 50197-1 obtained from Pretoria Portland Cement (PPC) was used. Fly ash (FA) obtained from AshResources, Lethabo plant located in Sasolburg, silica fume (SF) obtained from Mapei South Africa, and ground granulated blast-furnace slag (GGBS) obtained from Afrisam Vandebijlpark plant were used as cement replacement in various proportions as indicated in Table 3.1 conforming to SANS 1491:1, SANS 1491:2 and SANS 1491:3. Both fine (unwashed crusher sand) and coarse (22.4 mm) aggregates were obtained from Eikenhof plant of Afrisam cement; 12 mm high yield reinforcement was used for corrosion series batching while tap water available at the laboratory conforming to SANS 2001-1:2007/EN 1008 was used for casting all concrete specimens. The water/binder (W/B) ratio, fine and coarse aggregates ratio were kept constant for all the design mixes while the cementitious blends were varied according to the study objective. The control specimen is 100% OPC while other mixes contained different proportion of cementitious blends as indicated in Table 3.1. Sample descriptions was presented in Table 3.2. The sieve analysis of both coarse and fine aggregates was carried out in accordance with the SANS 201:2008 as presented in Table 3.3, and 3.4 respectively. The chemical composition, and physical properties of OPC, FA, GGBS, and SF used during the investigation is presented on Table 3.5 as per SANS 50450 – 1. Reagents used for the corrosion tests during the experimental work are ordinary portable water, distilled water, sodium chloride (NaCl), and magnesium sulphate ($MgSO_4$).

The test schedule for both the workability, compressive strength, oxygen permeability, sorptivity, and chloride conductivity were presented in Table 3.6 while pH, and voltage were presented in Table 3.7.

Table 3.1: Mix design for 1m^3 concrete for both compressive, durability, and corrosion tests.

No.	Mix ID	Cement Content by percentage (%)				Cement Content by mass (kg/m^3)				Water Content (kg/m^3)	Fine agg content (kg/m^3)	Coarse agg content (kg/m^3)
		OPC	SF	FA	GGBS	OPC	SF	FA	GGBS			
1	Control	100	-	-	-	420	-	-	-	210	824.66	1091
2	CSFB7111	70	10	10	10	294	42	42	42	210	824.66	1091
3	CSFG4114	40	10	10	40	168	42	42	168	210	824.66	1091
4	CSFG4123	40	10	20	30	168	42	84	126	210	824.66	1091
5	CSFG4132	40	10	30	20	168	42	126	84	210	824.66	1091
6	CSFG4411	40	40	10	10	168	168	42	42	210	824.66	1091
7	CSFG4312	40	30	10	20	168	126	42	84	210	824.66	1091
8	CSFG4213	40	20	10	30	168	84	42	126	210	824.66	1091
9	CSFG4141	40	10	40	10	168	42	168	42	210	824.66	1091
10	CSFG4231	40	20	30	10	168	84	126	42	210	824.66	1091
11	CSFG4321	40	30	20	10	168	126	84	42	210	824.66	1091
12	CFGPD325	30	-	20	50	126	-	84	210	210	824.66	1091
13	CGMR5005	50	-	-	50	210	-	-	210	210	824.66	1091
14	CS7300	70	30	-	-	294	126	-	-	210	824.66	1091
15	CS9100	90	10	-	-	378	42	-	-	210	824.66	1091
16	CSG5104	50	10	-	40	120	42	-	168	210	824.66	1091

Table 3.2: Samples Description

Mix No	Mix ID	SCMs % Composition	Previous reference works
1	Control	100%OPC	Mix Number 12 – 16 which represents previous work similar to this study were also repeated to form the basis of benchmarking and validation of this investigation though they were not carried out under the same environmental conditions.
2	CSFG7111	70%OPC+10%SF+10%FA+10%GGBS	
3	CSFG4114	40%OPC+10%SF+10%FA+40%GGBS	
4	CSFG4123	40%OPC+10%SF+20%FA+30%GGBS	
5	CSFG4132	40%OPC+10%SF+30%FA+20%GGBS	
6	CSFG4411	40%OPC+40%SF+10%FA+10%GGBS	
7	CSFG4312	40%OPC+30%SF+10%FA+20%GGBS	
8	CSFG4213	40%OPC+20%SF+10%FA+30%GGBS	
9	CSFG4141	40%OPC+10%SF+40%FA+10%GGBS	
10	CSFG4231	40%OPC+20%SF+30%FA+10%GGBS	
11	CSFG4321	40%OPC+30%SF+20%FA+10%GGBS	
12	*CFGPD3025	30%OPC+0%SF+20%FA+50%GGBS	CFGPD3025*/ P.Dinakar et al 2006 work
13	*CGMR5005	50%OPC+0%SF+0%FA+50%GGBS	CGMR5005* /Meusel & Ros work and SA
14	*CS7300	70%OPC+30%SF+0%FA+0%GGBS	CS7300* = Berry & Molhotra work and SA
15	*CS9100	90%OPC+10%SF+0%FA+0%GGBS	CS9100* = SA works
16	*CSG5104	50%OPC+10%SF+0%FA+40%GGBS	CSG5104* = SA Works

Table 3.3: **Sieve analysis of coarse aggregate with 22 mm maximum size used**

Total Mass 2624.5g	Sieve (mm)	Individual Mass Retained R	Individual % retained (R/total x 100)	Cumulative % (4750-150) sieves	% of material that passed	% of material that passed (rounded off)
	26.5	57.6	2.2	2.2	97.8	98
	19.0	1135.6	43.3	45.5	54.5	55
	13.2	1353.8	51.6	97.1	2.9	3
	9.5	70.5	2.7	99.8	0.2	0
	6.7	0.9	0.0	99.8	0.2	0
	4.75	0.4	0.0	99.8	0.2	0
	2.36	0.5	0.0	99.8	0.2	0
	1.18	0.3	0.0	99.8	0.2	0
	0.6	0.2	0.0	99.8	0.2	0
	0.3	0.2	0.0	99.8	0.2	0
	0.15	0.4	0.0	99.8	0.2	0
	0.075	0.5	0.0	99.8	0.2	0

Table 3.4: Sieve analysis of fine aggregates used

Total Mass 617.1g	Sieve Unit (mm)	Individual Mass Retained R	Individual % retained (R/total x 100)	Cumulative % 4750-150) sieves	% of material that passed	% of material that passed (rounded off)
	6.7	0.6	0.1	0.1	99.9	100
	4.75	49.8	8.1	8.2	91.8	92
	2.36	227.8	36.9	45.1	54.9	55
	1.18	127.9	20.7	65.8	34.2	34
	0.6	68.9	11.2	77.0	23.0	23
	0.3	41.4	6.7	83.7	16.3	16
	0.15	26.6	4.3	88	12.0	12
	0.075	18.1	2.9		9.1	9.1

Table 3.5: Chemical composition of binders used

Constituents (wt %)	**Fly ash**	**GGBS**	**OPC**	**Silica Fume**
Al_2O_3	16.4	6.6	2	0.8
CaO	2.4	20.7	35.2	1.1
Cu	0.3	0.3	0.4	0.3
Fe_2O_3	2.6	0.2	1.5	1.8
K_2O	0.6	1	0	2
MgO	0.5	4.4	1.1	1.2
Mn_2O_3	0	0.9	0.3	0.3
Na_2O	0	0.2	0	0.3
O	54.6	49.4	52.2	55.9
SiO_2	21.6	15	6.5	36.2
TiO_2	1.1	0.4	0	0
SO_3	0	0.7	1	0

This was obtained from the laboratory during investigation.

3.3 Test Schedules

Table 3.6 and 3.7 presented the test schedule tables of phase 1 and 2 respectively, indicating the total number of specimens prepared for the project, the test methods and the mould sizes.

Table 3.6: Test details of phase 1(Concrete)

Tests	**Sample size**	**Test age (days)**	**No of samples**	**Total**	**Test Method**
Slump	Fresh Concrete	After mixing	16	32	SANS 5862-1:2006
Compressive strength	150 mm cube	7, 14, 28, 90 and 120	15 cubes/mix	240	SANS 5863:2006
Oxygen permeability, sorptivity and chloride conductivity	150 mm cube	28, 90, and 120	4 cubes/mix	192	Method described by Alexander et al (1999)

Total Samples: 432 (150 x 150 x 150 mm)

Table 3.7: Test details of phase 2 (Concrete in the media)

Tests	**Sample size**	**Test age (days)**	**No of samples**	**Total**	**Test Method**
pH	150 mm cube	5 days interval	96	96	Half-cell techniques Ikotun and Afolabi (2013)
Voltage	150 mm cube	5 days interval			
Resistivity	150 mm cube	5 days interval			

Total Samples: 96 (150 x 150 x 150 mm)

3.4 Experimental Procedure

3.4.1 Mix proportion and preparation of the specimen:

Cubic plastic mould conforming to SANS 5860:2006 measuring 150 x 150 x150 mm with a 12 mm high yield steel bar placed centrally with an effective cover of 25 mm at the bottom was used for corrosion test series. This was achieved by measuring the height of the reinforcement from the top of the mould to the top edge of the reinforcement as indicated in Figure 3.5 to ensure the consistency of the bottom cover 25 mm. The rod was initially cleaned with a 600 grit sic emery paper and degreased with acetone. The constituents (aggregate, sand, cement, water with varying contents of cementitious blends) were mixed in a revolving mixer for 4 - 5 minutes according to SANS 50197-1 as shown in Figure 3.1 below. The percentage of the SCMs in the concrete mix were varied as shown in Table 3.1 from 0% to 60% in line with the objective of the study for both media (chloride and sulphate) which produced 96 beams and 432 cubes respectively. The chemical compositions of these SCMs is shown in Table 3.5 above. The total number of cubes for strength, durability and corrosion tests produced the total number of 528 cubes as shown in Table 3.6 and 3.7 respectively.

Particle relative densities, compacted bulk densities of the aggregates and the Fineness Modulus (FM) of the fine aggregates were determined in accordance with SANS 5847 prior to the trial mix. The coarse and fine compacted bulk density (CBD) was found to be 1648 kg/m^3 and 1860 kg/m^3 respectively. The Fineness Modulus (FM) of fine was found to be 3.68. The % Flakiness was conducted in accordance to TMH1 B3T and it was found to be 16.06%. Cement and Concrete Institute (C & CI) method was used to design trial mixes for the control specimen thereby verifying any assumptions and eliminate significant inaccuracy usually accompanying concrete design mix.

The binders used were CEM I 52.5N supplied by PPC cement; Fly ash supplied by Ash Resources as Durapozz, Silica fume was supplied by Mapei South Africa, and ground granulated blast furnace slag supplied by Afrisam as slagment. The chemical composition of each binder is given in Table 3.5 above. Prior to casting, both the coarse and fine aggregates were oven dried at a temperature of 110^{o}C for 24 hours as indicated in Figure 3.2.

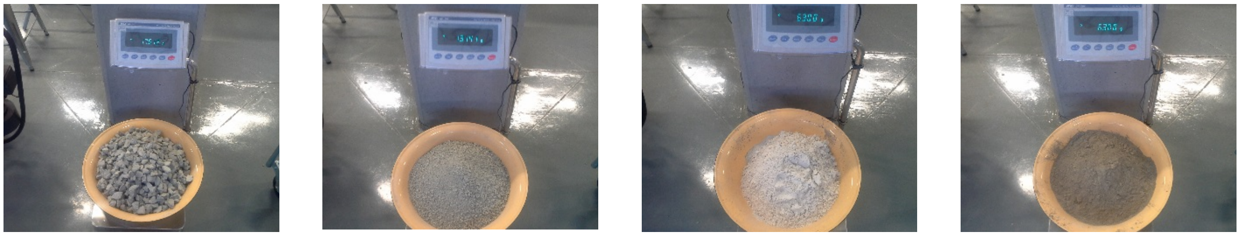
Cementitious materials, coarse aggregate, unwashed crusher sand, and water were weigh batched on a laboratory balance to an accuracy of 100 g as shown in Figure 3.3. For all mixes, three test samples of 150 mm size were prepared and cured with reference to SANS 5861-2 and SANS 5861-3. Compressive testing was performed according to SANS 5863-2006 for (7, 14, 28, 90 and 120) curing days respectively. While four cube specimens of 150 mm size were cast for durability test per each test days (28, 90 and 120) respectively. Also, three reinforced concrete cubes (150 x 150 x 150 mm) per test series as shown in Figure 3.4 below was cast for corrosion potential measurements in the two different media mentioned above making a total six sample per test series. Before casting, each mould was thinly coated with greased to prevent leakage or water through the joints and to prevent the adhesion of the concrete to the mould with reference to SANS 5861-3:2006.

Immediately after casting, the concrete samples were wrapped in polythene bags for proper curing for 24 hours prior to demolding as shown in Figure 3.3b. After demolding, the cubes were cured in portable water under a control temperature range of 22-25ºC for 7, 14, 28, 90 and 120 days respectively in a curing bath before testing. The beams were air cured for 24 hours prior to immersion in a tank containing constant concentration of 0.5 M of sodium chloride and Magnesium sulphate solutions respectively. The solution was kept constant such that 90% the depth of the sample was immersed in the solution at all times as shown in Figure 3.4 below:

(a) (b)

Figure 3.1: (a) Empty mixing drum (b) Concrete constituents in a mixing drum

Figure 3.2: Aggregates in an oven dry process for 24 hours prior to casting



22 mm aggregates fine aggregates fly ash Portland cement

Figure 3.3a Batching materials on a weighing scale

Figure 3.3b Concrete covered with polythene material

Figure 3.4: Reinforced concrete beam in the media

3.4.2 Casting concrete specimens for strength and durability tests

The process of batching, weighting and mixing of concrete materials were carried out in accordance to SANS 5861-1. Before casting, each mould was thinly coated with grease to prevent leakage or water through the joints and to prevent the adhesion of the concrete to the mould with reference to SANS 5861-3:2006. Rotating pan mixer of 50 Litre capacity was used; firstly, both coarse and fine aggregates and cement were mixed for 30 seconds then water was added to the blended constituents and mixed for approximately 4 minutes. For every batch of fresh concrete, slump test, which is a function of workability, was performed in accordance with SANS 5862-2:2006. The slump used is a cone with 300 mm high and 203 mm diameter open base while its smaller opening at the top is 102 mm. The tools for slump test among others include slump mould; steel tamping rod, and flat steel plate were wiped with a damp cloth before carrying out the test. The slump mould was placed on the steel plate and held firmly by standing on its foot pieces. The slump mould was filled in three layers of equal depth. Each layer was tamped 25 times with the rounded end of the tamping rod. The excess concrete was struck off by means of a rolling motion of the tamping rod, such that the mould is filled and leveled. During the slump test, the mould was firmly held down by its handles on both side of the cone keeping it steady while stepping off the foot pieces. The mould was then lifted carefully away from the concrete.

The cone was then inverted and placed near slumped concrete. The slump was measured by determining the vertical difference between the top rim of the mould and the average highest point of the surface of slumped concrete. After slump test was executed, the used slump concrete specimens were poured back to the mixing pan and mixed again to enhance homogeneity of the concrete mix before being poured into the mould.

3.4.3 Casting of reinforced concrete specimens for corrosion test

The casting procedure adopted for corrosion test series was similar to the one described in section 3.2.2; but in this case, a twisted steel rod of 12 mm diameter high yield of 200 mm long were embedded centrally in the concrete sample as seen in Figure 3.5. A cover of 25 mm was given to the steel in the concrete. The reinforcing bar diameter were measured with digital clipper to confirm the diameter accuracy prior to casting and was polished with a 600 grit sic emery paper and degreased with acetone and air dried prior to its insertion into the mould before casting.

The reinforced concrete (RC) specimens were mechanically vibrated and were demoulded after 24 hours of casting, subjected to air dried curing for another 24 hours prior to its placement in the media. After curing period was over, all RC specimens were 90% immersed in 0.5M sodium chloride (NaCl) and 0.5M magnesium sulphate ($MgSO_4$) solution respectively. Specimens in triplicate were cast for each mix and the average of these values is reported and interpreted based on ASTM C 876-1999. The specimens were maintained under the same room temperature for 150 days. Sodium chloride and magnesium sulphate analytical reagent was used in the preparation of test solutions.

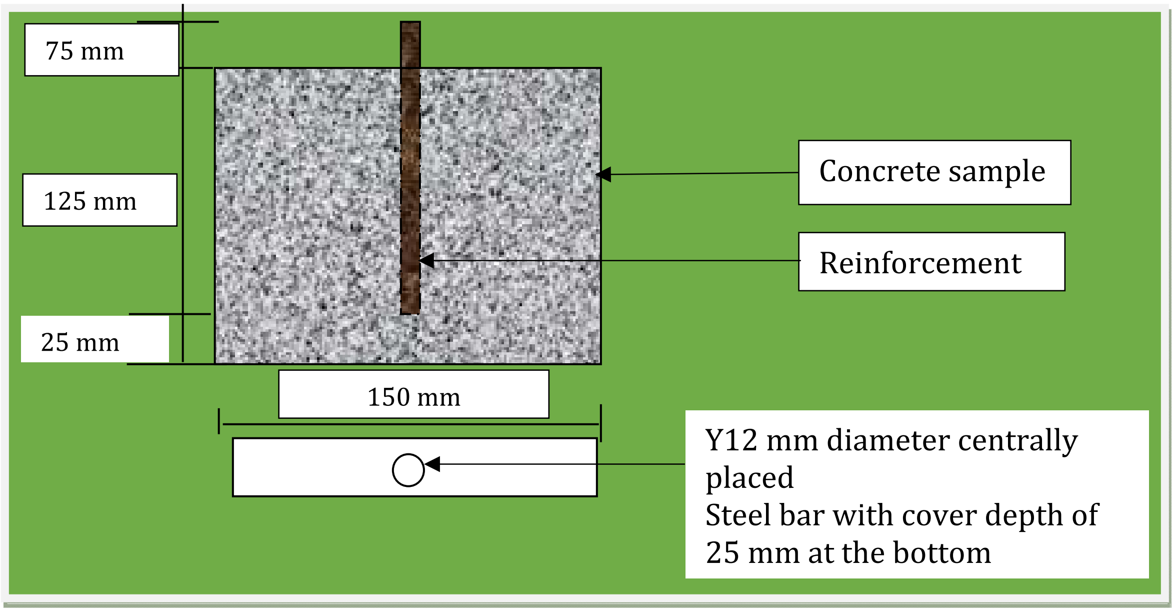


Figure 3.5: Reinforcement centrally placed in the SCM concrete sample

3.4.4 Compacting and Curing

Vibrating tables operated mechanically were used during the vibration to vibrate and compact the filled concrete mould as indicated in Figure 3.6a and b. The vibrating tables were such that the concrete mould could be fixed to ensure that the mould is clamped to the table. Vibration was applied for 10 minutes to achieve full compaction of the concrete, and this vibration period was applied consistently throughout the casting process.

All concrete specimens were cured with reference to SANS 5861-3:2006. Concrete specimens were covered with an impervious sheet few minutes after casting and were stored on a concrete table within the laboratory under a temperature between ± 23°C for a period of 24 hours after which they were demoulded and transfer into the control-curing tank maintained at temperature of ± 23°C. Figure 3.7a and b show concrete samples covering with impervious sheet few minutes after casting and samples in the curing tank respectively.

(a) (b)

Figure 3.6: (a) Concrete mould clamped to the vibrating table
(b) Concrete specimen on the vibrating table during vibration

(a) (b)

Figure 3.7 (a) Fresh concrete covered with impervious material
(b) Concrete specimen in a temperature control-curing tank

3.4.5 Oxygen permeability, sorptivity and chloride conductivity tests

The measurements of permeability, sorptivity, and chloride conductivity obtained under this investigation were meant to assess the durability performance of the indicative samples. The oxygen permeability index (OPI) test is a measure of the degree of pore connectivity in a concrete matrix, while sorptivity measures the rate of movement of waterfront through the concrete under capillary suction. The higher the OPI value, the lower the permeability of the concrete specimen.

The durability tests namely permeability, sorptivity and chloride conductivity were conducted on discs' samples with a diameter of 68 mm and thickness of 30 ± 2 mm, which, were core, drilled from the cover zone of the 150 mm cubes samples, after the curing maturity age of 28, 90, and 120 days. The disc specimens were subjected to an oven temperature at 50°C for 7 days before testing. Brief descriptions of the tests are given below:

3.5 Samples preparation

3.5.1 Testing for oxygen permeability

This test was carried out using a falling head gas permeameter (Ballim, 1991), and is based on Darcy coefficient of permeability determined by monitoring a falling pressured head. The samples consisted of discs of diameter 68 ± 2 mm and thickness 25 ± 2 mm. At testing age, these were core drilled from 150 mm cubes (parallel to the casting direction) as indicated in Figure 3.8(a) after being water-cured for required testing days (28, 90 and 180) respectively. Discs samples cored from the cubes were then oven dried at 50°C for 7 days prior to testing. The specimens were then removed from the oven and allowed to cool for 2 hours in a control room temperature at ± 23 °C. The thickness of each sample was measured with digital caliper at 4 points equally spaced around the perimeter of the specimen, while the diameter was measured at 4 points respectively as shown in Figure 3.8(b).

After the thickness and diameter of specimens had been recorded, the specimens were placed in a compressible collar indicated in Figure 3.8(c) with the test face (outer face) facing down. The collar was placed in a PVC sheath to form a unit as shown in Figure 3.9. This unit was placed in the permeameter chamber covered with a wooden ring and tightened. The complete experimental set up is shown in Figure 3.9**.** This test was performed at technical laboratory of AFRISAM in Roodepoort, South Africa in line with durability index approach developed by Ballim and Alexander (2005).

Figure 3.8: (a) (b) (c) Core drilled concrete specimens

Figure 3.9: A complete experimental setup

The oxygen pressure in the permeameter chamber has to be increased to 100 kPa before the inlet valve was closed. The variables of pressure and time were then recorded accordingly. Pressure delay was recorded at approximately 5 kPa intervals, and test stopped after 6 hours from start of test or when the pressure reaches approximately 60 kPa. The disc's specimens were removed from the collar and later used for sorptivity test once the permeability test has been concluded. The permeability coefficient (m/s) is deduced from the equation below:

$$K = \frac{WVg}{RA}\left[\frac{d}{\Theta .t}\right] \; \text{In} \left[\frac{Po}{P}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where:

K = coefficient of permeability in m/s

W = molecular mass of oxygen, 32 g/mol

V = volume of oxygen under pressure in permeameter (m^3)

g = acceleration due to gravity, 9.81 m/s^2

R = universal gas constant, 8.313 Nm/Kmol

A = superficial cross-sectional area of sample (m^3)

d = average sample thickness (m)

θ = absolute temperature (K)

t = time (s) for pressure to decrease from Po to P

Po = pressure at the beginning of test (kPa)

P = pressure at the end of test

Note that results recorded are average of three specimens

3.5.2. Testing for Sorptivity and Porosity

After the permeability test, the same disc specimens were used for water sorptivity test, following the procedure stipulated by Ballim and Alexander, 2005. The curved surface of the specimen was wrapped with tape up to 5mm above test face as indicated in Figure 3.10a; this allows only one directional capillary flow of water to occur. The test face of specimens was placed in calcium hydroxide solution contained in a tray as indicated in Figure 3.10a such that the final level of solution was slightly above the edge of the test specimens. These specimens were weighed at regular of 3, 5, 7, 9, and 12 for a period of up to 25 minutes. This was followed by vacuum saturation of specimens done by applying 75 kPa suction as shown in Figure 3.10b.

Vacuum was applied for 3 hours to specimens placed in an empty dessicator followed by one hours fifteen minutes of vacuum suction while specimens were submerged in $Ca(OH)_2$ saturated water. After a further 18 hours of soaking, the specimens were weighed. Porosity was then calculated using equation 3.2 below.

$$n = \frac{Msv - Mso}{A.d.pw} \quad \text{...(3.2)}$$

Where:

Msv = vacuum saturated mass of the samples to the nearest 0.01

Mso = initial mass of the specimen to the nearest 0.01g

A = cross-sectional area of the specimens to the nearest 0.02m^2

d = average specimens thickness to the nearest 0.02 mm

Pw = density of water

The mass of the water absorbed at each weighing period is calculated using equation below:

$$M_{wt} = M_{st} - M_{so} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.3)}$$

Where:

M_{st} = mass to the nearest 0.01 g of the specimen at time t

Sorptivity was calculated from the slope of graph of water absorbed (M_{wt}) versus the square root of time (in hour)

$$S = \frac{F.d}{M_{sw} - M_{so}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots ..\text{(3.4)}$$

Where:

F = the slope of the best fit line obtained by plotting Mwt against $t^{½}$

S = sorptivity

(a) (b)

Figure 3.10(a) Disc specimen sealed with tape

Results recorded are average of three samples

3.5.3. Chloride conductivity Index (CCI) test

The preconditioned samples as mentioned in section 3.3.2 above were allowed to cool for two hours before subjected to a vacuum saturation in a 5M sodium chloride solution for another four hours and allowed to soak for another 18 hours. Each sample was then placed in a rubber collar contained within a rigid plastic ring. The anode and cathode chambers were filled with salt solution; these chambers were then screwed to the rigid plastic ring such that no solution leakage is experienced from the conduction cell. The conduction cell was then connected to the ammeter and voltmeter after being placed horizontally. A 10 Volt (V) potential difference was applied across the sample to accelerate the movement of chloride ions, and at the same time, the current flowing through the concrete specimen was measured. The test setup is shown in Figure 3.11.

Figure 3.11: Experimental Set up for CCI

3.5.4 Compressive strength test

Under this study, the concrete specimens were of the same size and shape. To determine the compressive strength test, test procedure conforming to SANS 5863:2006 was applied. Loading speed of 0.3 MPa/s was applied consistently to all the testing specimens according to SANS 5863: Clause 5.3 2006. At every testing age (7, 14, 28, 90, and 120 days), concrete specimens were removed from the temperature control curing tank and weighed once excess water had been wiped off the surface with dry cloth. The specimen mass was recorded before centrally placed in a compressive testing machine and load was applied in a compression test machine at a rate of

150 kN/m. The uniaxial load was applied perpendicular to the direction of casting face. Failure load was recorded to the nearest one kN. Compressive strength test was done using Toni/Tecknic compressive testing machine originated from Germany conforming to EN 12390-3 standards with a load capacity of 3000 kN. Figure 3.12 show the loading to failure of specimen during testing.

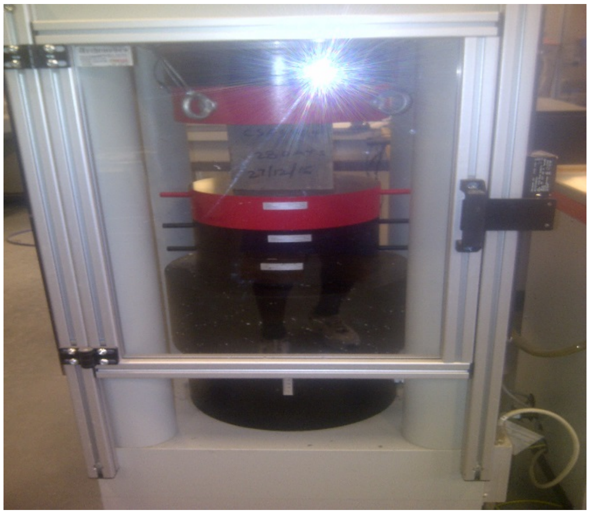


Figure 3.12: concrete specimen undergoing crushing test

Compressive strength was determined at curing ages of 7, 14, 28, 90 and 120 days respectively and was calculated in N/mm^2 using equation 3.5: Table 3.8 shows the average reading of three samples for each casting series.

$$R_c = \frac{F_c}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

Where:

Rc is the compressive strength in Newton per square millimeter (N/mm^2)

Fc is the maximum load at fracture, in Newton (N)

A is the area of the load bearing plates, in square millimeter (mm^2

3.5.5 Electromechanical measurements

The electrochemical measurement according to the procedure followed by Ikotun and Afolabi, 2013 was applied, test specimens was partially immersed in a solution of 0.5M sodium chloride and 0.5M Magnesium sulphate respectively. The electrode potential of each of them was recorded at a 5-day interval for 150 days using a high impedance digital voltmeter with zinc rod as the reference electrode as shown in Figure 3.13. The first (working electrode) terminal was in contact with the reinforced concrete immersed in the corrosive medium. This process was repeated for each sample in each medium. The voltage reading on the meter then gives the potential of the reinforcement and converted to saturate calomel electrode (SCE) using the relation in equation 3.6:

Electrode PotentialmV (SCE) = (Ezn – 1030) ……………………………………….(3.6)

Where Ezn is the electrode potential of zinc reference electrode

The reason for using this method is that it has been found to be a valid indicator of corrosion activity (Rasheeduzzarfar, 1986) and the performance of specimens could be compared by measuring the time needed for an abrupt increase in potential value.

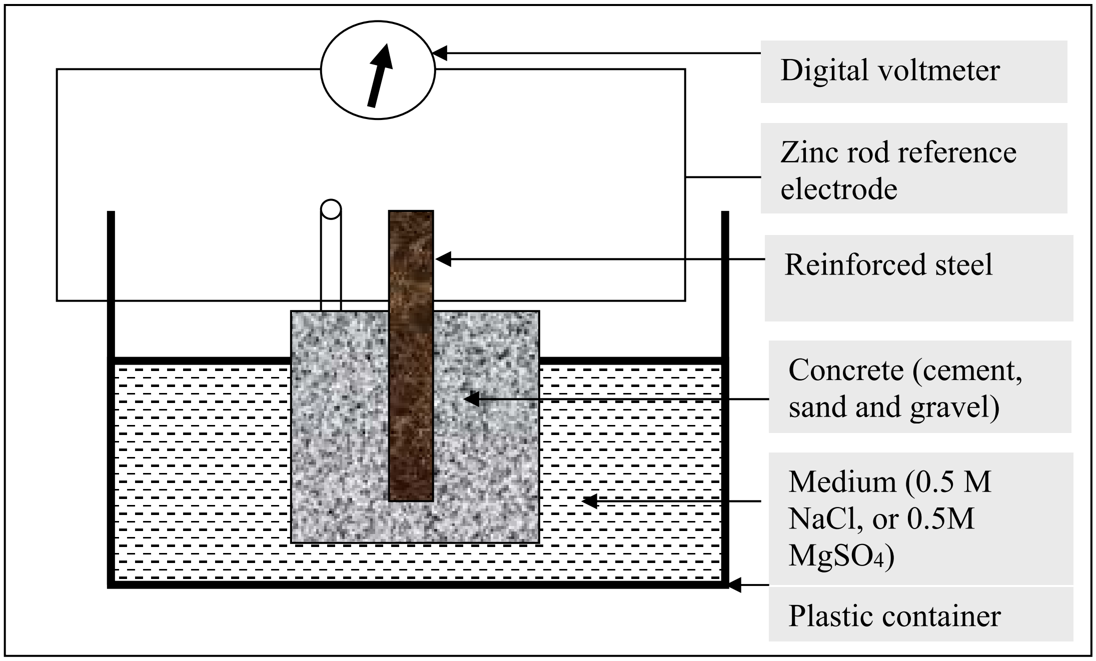


Figure 3.13: Experimental set-up showing electrode potential measurement.

3.5.6 Weight Loss Test

The coupon from each reinforced concrete sample were tested after they were removed from the media (0,5M Nacl & $MgSO_4$) on 167, 172, 177 days respectively. The reinforcement steel were removed from the concrete sample with the aid of splitting tensile machine and the steel were cleaned of all corrosion products and were reweighed. The weight loss was converted to a corrosion rate (CR) using equation 3.7

$$Corrosion\ Rate\ (CR) = \frac{Weight\ loss\ (g)\ x\ K}{Alloy\ Density\ (g/cm^3\ x\ Exposed\ \ Area\ (A)\ x\ Exposure\ Time\ (Hr)} \qquad ----(3.7)$$

Where:

Weight loss is the change in weight in grams
$K = 8.75x10^4$
Area = the surface area of the coupon in cm^2
Exposure Time in hour
Material density = $7.85g/cm^3$

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the results obtained from the different tests performed in this project. Strength development of concrete has direct correlation to the temperature and humidity conditions subjected to during curing period. It becomes evident that higher temperature increases the speed of chemical reaction and thus the rate of strength development. However, achieving higher strength at later age depend on prevention of loss of water from the concrete (Teychenne, et al. 1997). The properties of fresh concrete are those that affect concrete ability to transport, handle, place, and finish. For hardened concrete to meet its structural and durability requirements, fresh concrete must satisfy certain requirements such as workability, segregation and bleeding (Ikotun, 2009).

The cement class and water/cement ratio also play important roles in the compressive strength of the concrete. Table 4.1 shows the approximate compressive strength (MPa) of concrete mixes made with a free-water/cement ratio of 0.5 for different curing ages using class 52.5 and 42.5 respectively.

Table 4.1: Approximate compressive strengths (MPa)) of concrete mixes made with a Water/cement ratio of 0.5

Cement strength class	Type of coarse aggregate	Compressive strengths (MPa)			
		Age(Days)			
		3	7	24	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Source: Design of normal concrete mixes second edition. Marsh B.K. 1988 BREPress

4.2 Workability

The workability results are shown in Figure 4.1. The percentage inclusion of various extenders played a big role in the workability performance of the mixes. The effect of GGBS, FA, and SF was observed such as the improvement of workability as the GGBS increases; also, reduction of workability as SF increases. The higher the percentage of SF content, the stickier the sample; hence the reduction of workability of the sample under investigation. It was evident that extenders proportionality influences the slump results as depicted in Figure 4.1. To improve the workability of the samples, admixture can be added: but this was not done in this work so as not to interfere with the effect of the SCMs on the concrete strength. The W/B ratio was restricted to 0.5 because excess addition of water will also have adverse effect on the strength and will jeopardise the objective of this study. All samples were compacted on the vibrating table consistently to ensure that well compacted concrete was formed even with low slump experienced.

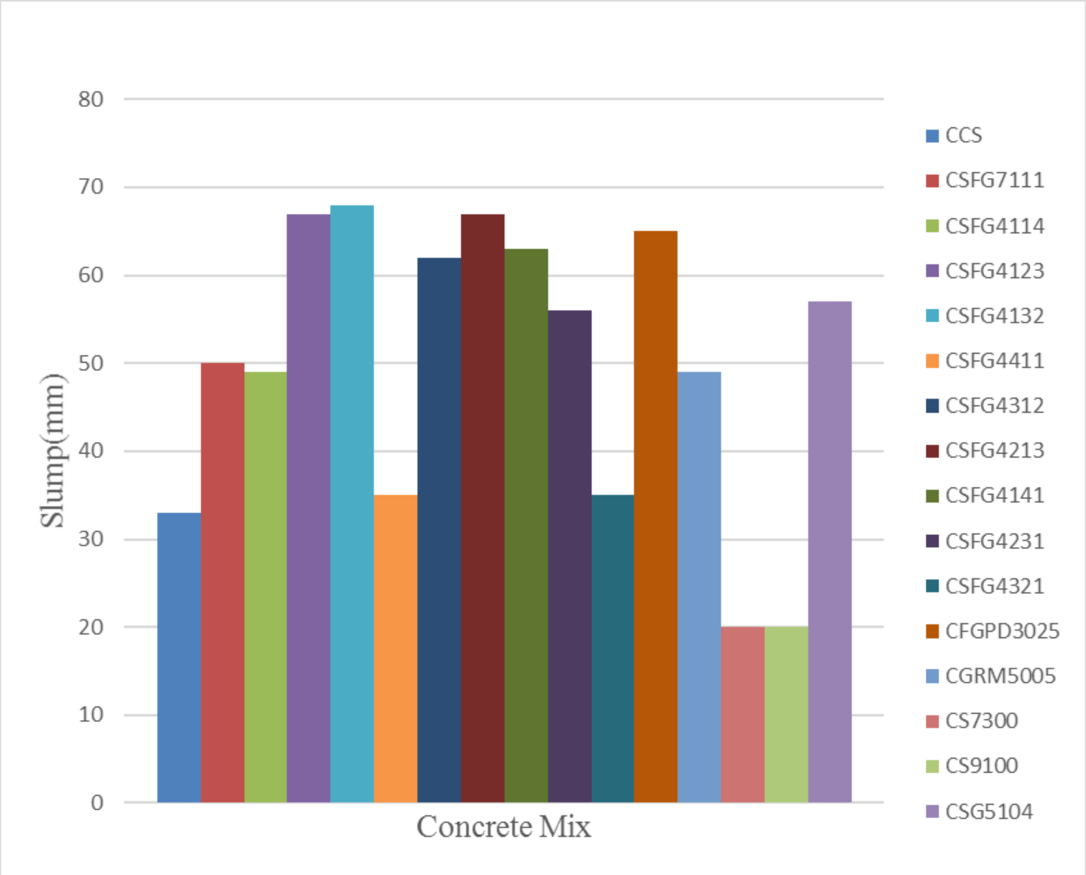


Figure 4.1: Workability of concrete samples under investigation

4.3 Compressive strength development

At the early ages, both the quaternary, ternary and binary blended samples showed slightly lower strength than the corresponding control sample made with 100% OPC. This development could be attributed to the slower rate of hydration in the blended samples, with increase in age, the pozzolanic reaction increases and consequently rate of strength increases for all the mixes for 7 days over 14 days samples ranges from 60% - 85% compared to control sample which stand at 99%. It is observed that the higher the curing days, the lower the rate of strength increase. Table 4.2 shows the strength results and the % increase in strength for all the concrete samples between 7 & 28 days curing period. It can be seen from Table 4.2 that as the age increases, the compressive strength also increases for most of the samples; but interestingly, there is a 3%, 2%, and 1% strength decrease in control sample and CSFG4411 and CSG5104 respectively after 90 days curing.

Table 4.2: Workability and strength of the concrete specimen cured in a water.

S/No	MIX ID	Slump (mm)	Compressive Strengths (MPa)						% increase in strength bet 7 & 28 days	% increase in strength bet 7 & 120 days
			7 days	14 days	28 days	90 days	120 days	W/B		
1	Control Sample	33	56.19	57.02	60.05	70.59	68.30	0.5	6.63%	22%
2	CSFG7111	50	30.12	43.37	49.95	55.83	60.89	0.5	65.84%	99%
3	CSFG4114	49	20.89	30.95	37.26	52.00	52.02	0.5	78.36%	149%
4	CSFG4123	67	20.20	31.24	41.12	48.88	56.13	0.5	103.56%	178%
5	CSFG4132	68	17.46	28.94	36.75	45.87	52.22	0.5	110.48%	199%
6	CSFG4411	35	20.56	29.46	32.20	48.25	47.23	0.5	56.61%	130%
7	CSFG4312	62	16.75	27.82	38.29	44.71	45.72	0.5	128.6%	173%
8	CSFG4213	67	19.10	29.90	36.90	50.09	54.69	0.5	93.19%	186%
9	CSFG4141	63	16.22	26.07	35.14	47.57	48.95	0.5	116.65%	202%
10	CSFG4231	56	18.11	26.29	33.04	42.68	42.86	0.5	82.44%	137%
11	CSFG4321	35	24.40	35.30	39.75	52.69	50.06	0.5	62.91%	105
12	CFGPD3025	65	22.41	31.51	37.00	46.26	46.83	0.5	65.1%	109
13	CGRM5005	49	30.41	42.36	48.02	63.94	65.61	0.5	57.91%	116
14	CS7300	20	37.49	46.43	52.10	59.63	62.03	0.5	38.97%	65
15	CS9100	20	45.08	53.13	60.01	65.02	67.87	0.5	33.12%	51
16	CSG5104	57	13.69	21.29	28.10	40.49	39.96	0.5	105.26%	192

4.3.1 Effect of supplementary cementitious materials on compressive strength

The mixture of different supplementary materials produced substantial amount of compressive strength compared to the control sample at 100% OPC as shown in Figure 4.2. The combination of 30% SF, 20% FA, 10% GGBS and 40% OPC (CSFG4321) produced the highest compressive strength of 24.40MPa, which is 43.4% of the control sample at 7 days. However, the combination of 10% SF, 20% FA, 30% GGBS and 40% OPC (CSFG4123) produced the highest strength of 41.12 MPa at 28 days which is 69% of the control sample strength at that age. At all ages, the blended samples showed lower strength results than the control sample made with 100 % OPC. However, the rate of strength increase from age to age is higher in blended samples than the control sample. This development could be attributed to the slower rate of hydration in the blended samples.

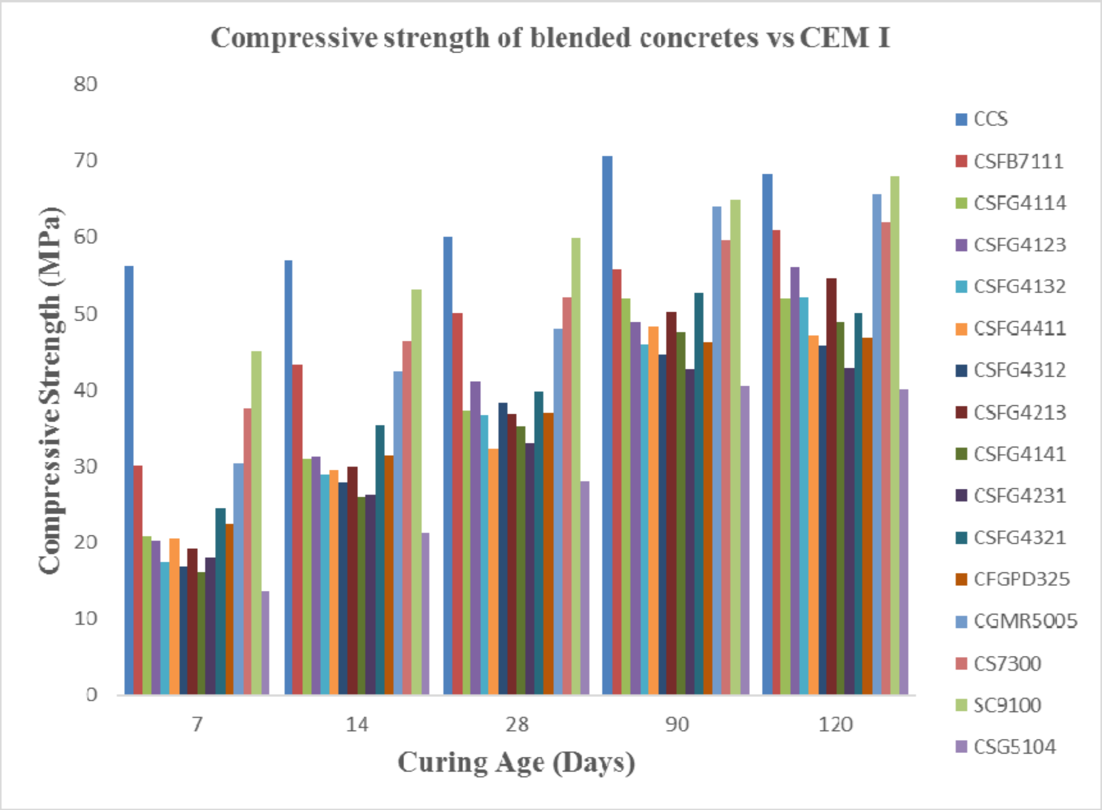


Figure 4.2. Compressive strengths for different ages

The binary combination of CS9100 (Mix 15), and quaternary combination of CSFG7111 (Mix 2) produced the highest strength of 67.87MPa and 60.89MPa respectively for all the supplementary blends at 120 days curing age as against the control sample of 68.3MPa maintained at 100% OPC at the same curing age. The results obtained showed that the rate of increase in strength as curing age progresses is higher for SCMs specimens than for the control specimen. The reported strength values represented the average strength of three specimens for each mix combination.

The lower early strength obtained in the SCMs specimens compared to the control specimen can be attributed to the effect of the pozzolanic reactions on specimens containing SCMs. From all the new mix proportions (40% OPC), specimens CSFG4123 and CSFG4321 showed approximately similar results (highest) at all ages, but specimen CSFG4321 showed a slight decrease in strength at 120 days curing, while for specimen CSFG4123, increase in strength was observed at 120 days curing. This was expected because GGBS is hydraulic in nature and has higher content in specimen CSFG4123 than CSFG4321. These observations also indicate that large quantity of SF in the SCMs mixture may result to adverse strength behaviour at the later age.

This trend (reduction in 120 days strength result) was also observed for specimen CSFG4411 where the content of SF is 40%. This observed behaviour may be attributed to the nature of the SF of reducing workability at higher content, as hydration continues, the water needed for further pozzolanic reaction will be reduced and ultimately reduced strength. The workability results confirmed this trend, for specimen CSFG4123, the workability is 67 mm, while for both specimens CSFG4321 and CSFG4411, the workability is 35 mm.

In all the combinations tested, control sample with 100%OPC gave better compressive strength irrespective of age. At the age of 120 days, compressive strength CS9100 (binary) was found to be almost matching. Similar to the trend observed in CS9100 and control sample at 120 days, the same performance was observed at 150 days projected result using Metwally et al. 2014 model.

In general, specimens with 60% OPC replacement may not be desirable due to the low strength results obtained over the ages compared to the control sample. Further tests on durability and corrosion resistance will give more insight on the behaviour of these mix proportions. The quaternary combination of CSFG7111 (Mix 2) with 10% each of the SCMs gave highest compressive strength values for all the days tested compared with all other mixtures having all the SCMs. The values at 120 days is 89% of the result obtained for the control specimen. This shows that generally, optimum mix proportion is of paramount important in combining different SCMs in concrete. The advantage of combining these SCMs will go beyond the strength value and extend to their durability behaviour. The results showed that the specimen with 10% each of the SCMs in the mix (CSFG7111) showed increase in strength at a desired rate compared to the control specimen. It was observed that this mix proportion (CSFG7111) showed 54% strength of control specimen at early stage (7 days) and 89% strength of the control specimen at later age (120 days). This is an indication that for this specimen, strength value beyond 120 days curing may be higher or approximately the same when compared with the control specimen.

4.3.2 Performance of 60% replacement concrete samples

The performance of the 60% SCMs replacement compared to the control specimen is shown in Figure 4.3. Looking specifically into the compressive strength of specimens blended with 60% OPC replacement, specimens made with 30%SF + 20% FA show the highest performance of 24.4MPa at 7 days followed by 20.2MPa for a concrete mix containing combination of 40%SF + 10%FA. The performance of the GGBS-containing mixture of 30% (CSFG4123 & CSFG 4213) at 7 days were more impressive compared to other mixes.

At the early age of 7 days, all the GGBS mixtures up to 30% attained lower compressive strength, but were superior to that of CSFG4141, CSFG4231, and CSFG4312 respectively. The performance of GGBS specimens suggested that latent hydraulic reactions by GGBS influence the development of compressive strength with an increase in GGBS content at the early age as alluded to by Yeau, K.Y et al. 2005. The results also show that the higher the GGBS contents in the mix, the lower the strength at 7 days. This might be due to the slow hydration reaction of slag, unlike FA; slag's reactivity is dependent more on temperature (Miura, T. et al. 2000). However, at later period of 28 and 120 days, the compressive strength of the GGBS concrete mixture show a superior performance of 41.12 MPa and 56.13 MPa compared to other specimens respectively. It is also interesting that the concrete specimens, CSFG4123, CSFG4213 containing 30% GGBS show a strong performance compared to other mixes at 120 days. Specimens containing 30%SF and 30%FA (CSFG4321, CSFG4132) show similar strength improvement at both 28 and 120 days respectively. The performance of CSFG4321 at 7 days could be attributed to the influence of 30% content of silica fume as the addition of SF increases the early strength of concrete while reducing its permeability (Duval, R. et al. 1998).

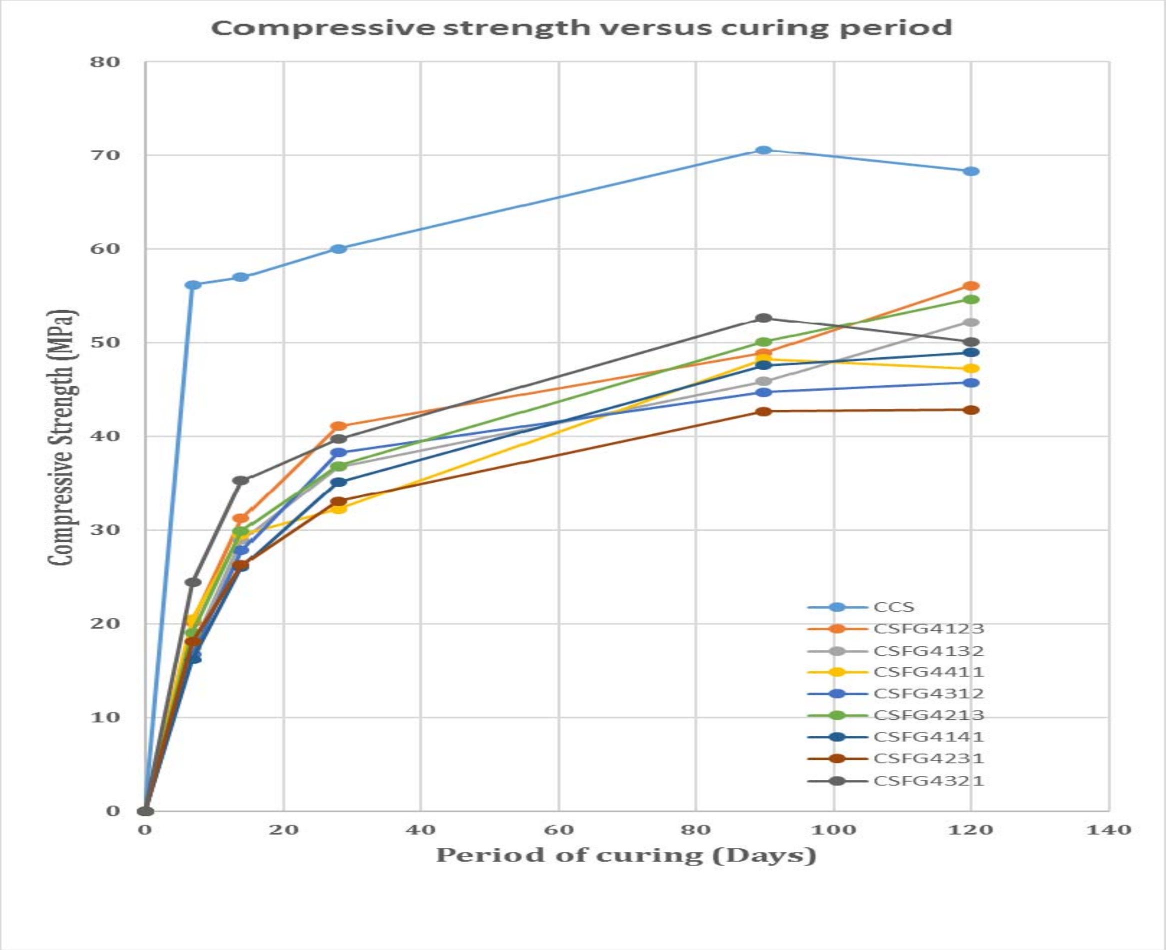


Figure 4.3: Compressive Strength of blended cements versus Curing Period

4.3.3 Effect of aggressive media as a curing medium on the compressive strength

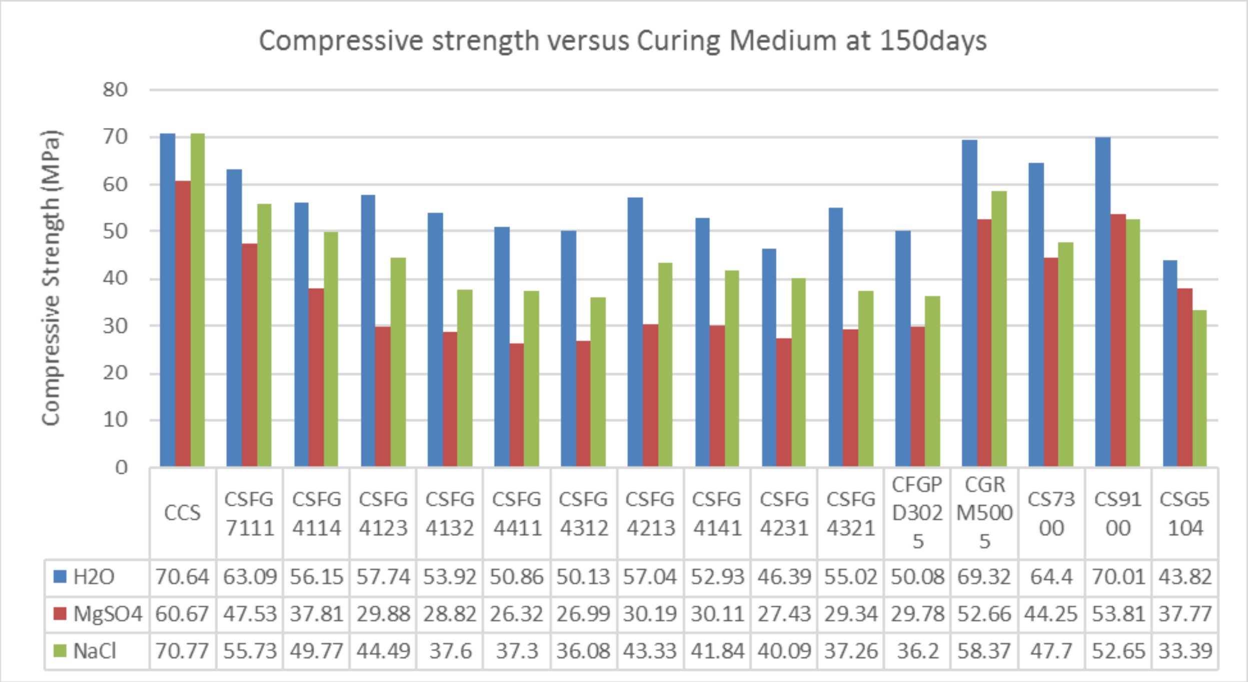
The compressive strength of reinforced concrete samples illustrated in Figure 4.4 indicates that after long exposure time, the sulphate attack was more severe than samples exposed to chloride environment. A comparison of the results shows that all samples cured in Sodium Chloride (NaCl) have higher strength than samples cured in sulphate media. This is in agreement with findings by Hassan et al., 2013. There were exceptions for binary samples CS9100 and ternary samples CSG5105 cured in magnesium sulphate ($MgSO_4$) which gained more strength by 1.16 MPa (1.08%) and 4.38 MPa (6.16%) respectively over samples cured in NaCl. It is interesting to observe that the control sample cured in NaCl is negligibly higher than the sample cured in water (H_2O) by 0.1% while the control sample cured in $MgSO_4$ is less than the sample cured in H_2O by 7.6% at the same curing period of 150 days.

The results show progressive loss of compressive strength of concrete cubes for all the concrete mix as against the control samples, but there is a strength performance of samples cured in sodium chloride relative to samples cured in H_2O as against samples cured in magnesium sulphate. The same observation was reported by Akinsola, et al., 2012.

The strength decline pattern observed for concrete cured in $MgSO_4$ and NaCl compared to concrete cured in H_2O could be attributed to sulphate and chloride attack respectively, which subject the concrete samples to expansion thus leading to spalling and cracking observed at the surface layer. The concrete thus becomes liable to soft mud as the presence of potassium and magnesium sulphates (Ks, MgS) in salt water could be responsible for sulphate attack in concrete since they readily react with calcium hydroxide ($Ca(OH)_2$) present in the cement through the hydration of C_3S and C_2S (Bryant, et al., 1964).

It is also observed that concrete mix containing 60% OPC replacement cured in $MgSO_4$ suffer significant average strength loss of 56% compared to concrete samples cured in water as against 73% to concrete samples cured in sodium chloride. The outcome of this investigation conformed with the findings of Shetty et al., 2006 as the varying percentage strength increment depends solely on the cement brand and possible exposed aggressive environment.

The physical attack at the surface layer such as softening, was more pronounced on the concrete samples cured in $MgSO_4$, than that of NaCl. The chemical attack effect due to the reaction between the sulphate ions, and concrete constituents, resulted in swelling, and cracking, which permits easier access to aggressive elements. This might be responsible for the loss of strength in concrete samples cured in magnesium sulphate.



	CCS	CSFG 7111	CSFG 4114	CSFG 4123	CSFG 4132	CSFG 4411	CSFG 4312	CSFG 4213	CSFG 4141	CSFG 4231	CSFG 4321	CFGP D302 5	CGR M500 5	CS73 00	CS91 00	CSG5 104
🟦 H2O	70.64	63.09	56.15	57.74	53.92	50.86	50.13	57.04	52.93	46.39	55.02	50.08	69.32	64.4	70.01	43.82
🟥 MgSO4	60.67	47.53	37.81	29.88	28.82	26.32	26.99	30.19	30.11	27.43	29.34	29.78	52.66	44.25	53.81	37.77
🟩 NaCl	70.77	55.73	49.77	44.49	37.6	37.3	36.08	43.33	41.84	40.09	37.26	36.2	58.37	47.7	52.65	33.39

Figure: 4.4 Compressive strength versus curing medium (H_2O, $MgSO_4$, and NaCl)

4.3.4 Decrease trends for all concrete samples under investigation

The decrease trends for all the blended concrete samples cured in water for all the curing ages relative to the control sample are represented in Figure 4.5.

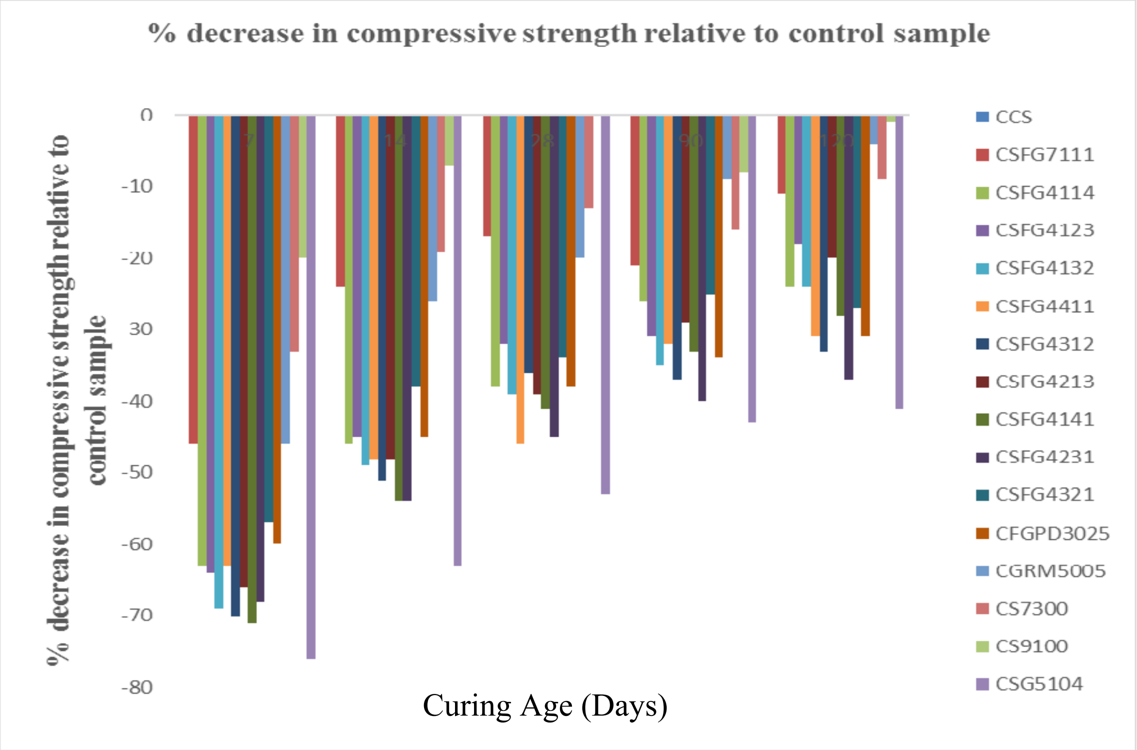
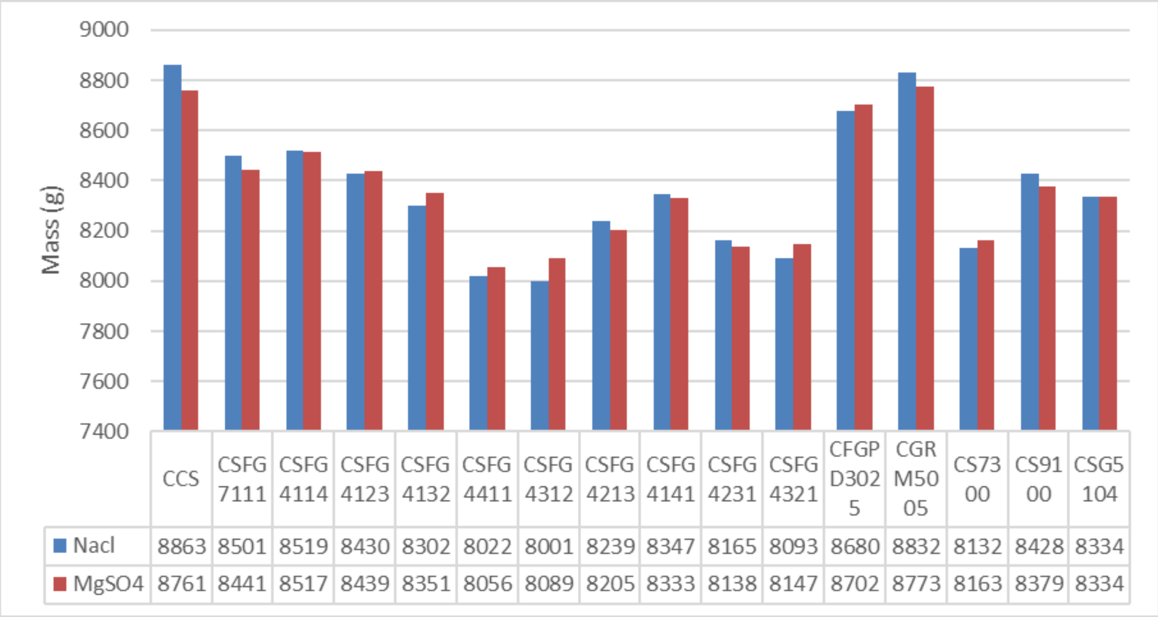


Figure 4.5: percentage decrease or increase in compressive strength of specimen relative to control

4.4 Effect of aggressive media (NaCl and $MgSO_4$) on change in mass

The change in mass for the concrete cured in sulphate up to 150 days compared with the change in mass of the concrete cured in chloride exposed to the same laboratory atmospheric condition is presented in Figure 4.6. The % ratio difference between the control samples cured in sodium chloride and magnesium sulphate recorded a minimal difference of 0.58% (Mix1) while there is no difference between the ternary mix containing 40% of GGBS cured in both medium (Mix 16). There is no significant mass difference in all the concrete mixes both in magnesium sulphate, and sodium chloride; but the mass of mixes containing 60% OPC replacement cured in sodium chloride has higher value than those cured in magnesium sulphate (refer to mixes CSFG4114, CSFG4213, CSFG4141, CSFG4231) with 0.02%, 1.1% ,0.08%, 0.16% respectively. The mass of some mixes containing same 60% OPC replacement cured in magnesium sulphate has higher value than those cured in sodium chloride (refer to mixes CSFG4123, CSFG4132, CSFG4411, CSFG4312, CSFG4321, with 0.06%, 0.3%, 0.22%, 0.54%, 0.34% respectively. It is interesting to observe that the mix containing equal proportion of supplementary cementitious materials of 10% has a percentage difference of 0.35% with a close of 0.34% (CGMR5005*)*.



	CCS	CSFG 7111	CSFG 4114	CSFG 4123	CSFG 4132	CSFG 4411	CSFG 4312	CSFG 4213	CSFG 4141	CSFG 4231	CSFG 4321	CFGP D302 5	CGR M50 05	CS73 00	CS91 00	CSG5 104
🟦 Nacl	8863	8501	8519	8430	8302	8022	8001	8239	8347	8165	8093	8680	8832	8132	8428	8334
🟥 MgSO4	8761	8441	8517	8439	8351	8056	8089	8205	8333	8138	8147	8702	8773	8163	8379	8334

Figure 4.6: Effect of aggressive medium (NaCl and $MgSO_4$) on change in mass

4.5 Durability of the concretes under investigation

4.5.1 Influence of blended concrete on oxygen permeability

Looking at the performance of the quaternary blended samples against the control sample presented in Figure 4.7, it is observed that the permeability of mix CSFG4312 containing 30%SF was significantly higher than other mixes including the control sample at both 28 and 90, days respectively. The results also show that samples CSFG4132 and CSFG4141 behave far better than control, these two samples has SF in low content.

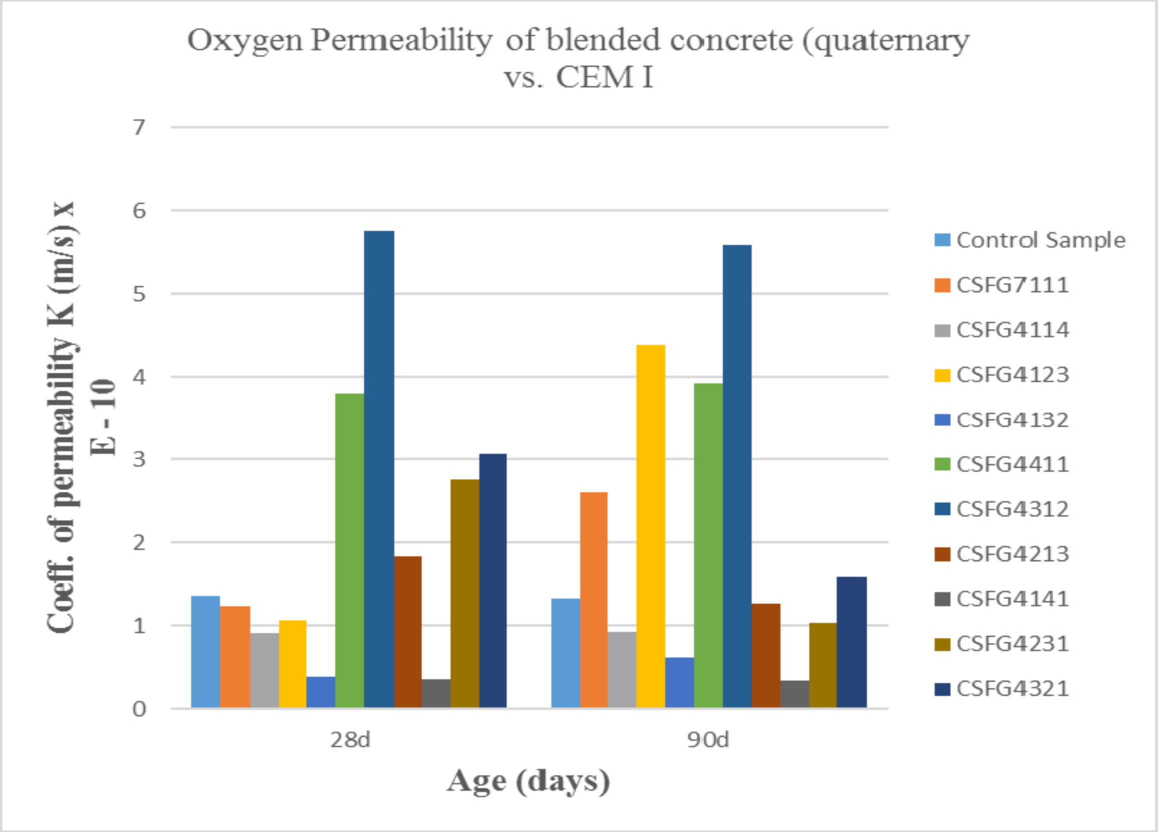


Figure 4.7: Coefficient of permeability of quaternary concretes samples

Kearsley et al. 2001 defined permeability as a good indicator of the quality of concrete because it indicates the ease with which fluids, gases, or vapours enter and move through the concrete. Permeability as reported by Real et al. 2017 depends on the porosity of cement paste (affected by the w/c ratio, hydration degree and the type of binders); aggregate and interfacial transition zone. (Ollivier et al. 1995; Bustos et al. 2015). It also depends on other factors such as cracks and voids, relative humidity (Kropp et al. 1995; Dinku et al. 1997; Bentz et al. 1999; Ollivier et al. 1995, Bustos et al. 2015, and Villain et al. 2001) and less significantly, temperature. (Kropp et al.

1995, Ollivier et al. 1995). Figure 4.7 to 4.10 present oxygen permeability at 28, 90 days respectively as a function of the percentage of cement replacement with different blended types of cement.

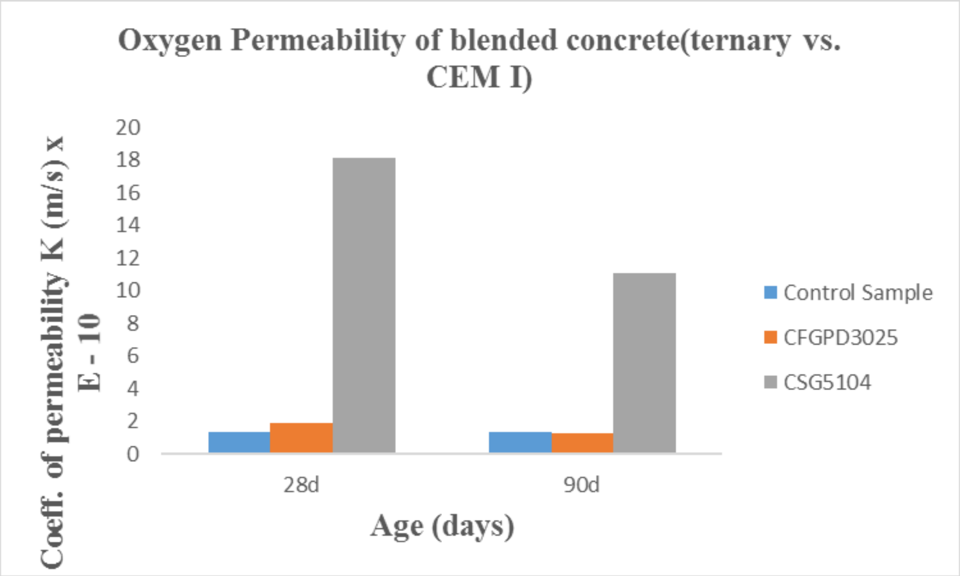


Figure 4.8: Coefficient of permeability of ternary concretes samples

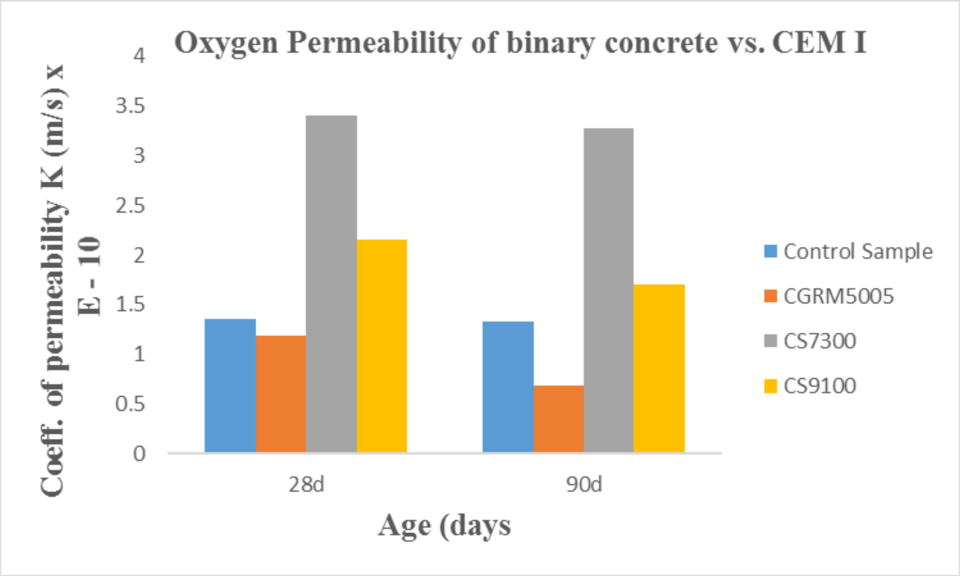


Figure 4.9: Coefficient of permeability of binary concretes samples

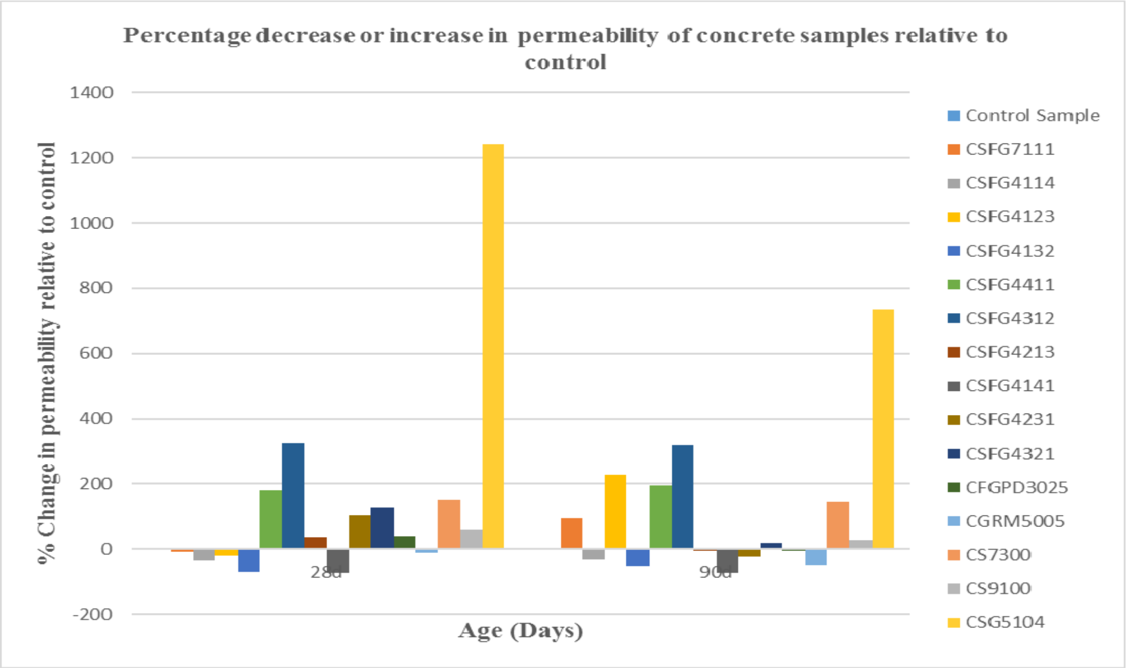


Figure 4.10: Percentage decrease or increase in permeability of concrete samples relative to control

The permeability of the mixes containing high content of SF tends to agree with the findings of Real et al. 2017 that SF was not efficient in refining the porous structure of cement paste, which could also be, confirmed from the results of compressive strength as indicated in the Table 4.2. Real et al. 2017 suggested that it is likely that there was no effective dispersion of SF in the mix even though better results would have been expected, as Guneysi et al. 2012 found 40% lower permeability when cement was partly replaced with 5% SF for concretes with w/b ratio of 0.35.

In the case of ternary blended concretes presented in Figure 4.8, it is observed that the mix (CSG5104) is more porous than both control and CFGPD3025 mixes. The combination of 70% OPC+30%SF has higher permeability than other blended concrete for binary concrete. It is interesting to note that mix CSFG4141 (w/b = 0.5) performed favourably with the works of Ballim et al. 2009 using CEM I 100% OPC sample (w/b = 0.4) measured on water-cured regime at 28 days. Likewise, mix CGMR5005 (w/b = 0.5) compared favourably with 50%CEM I + 50%GGBS sample with w/b 0.6 reported by Ballim et al. 2009.

The test results from Figure 4.10 shows that some blended concretes are less permeable than the control, this is consistent with the findings of Alexander et al. 2004. Also, CSFG4141 at 28 and

90 days respectively exceeds Grade 55 OPC concrete limit of (9.43 – 10.44), this could be attributed to the 40% content of FA in the mix (Alexander et al. 2004) as the FA or slag contents are found to be less permeable than plain Portland concrete. Although with few exceptions, most of the blended concrete samples under investigation can be said to be "deemed to satisfy" the durability requirements as the results falls within the acceptance limits for durability indexes as indicated in Table 4.3 below.

Table 4.3: Comparison between Acceptance Limits for durability indexes and results obtained from the investigation at 28 days

Acceptance Criterion	**OPI (log scale)**	**Sorptivity (mm/hr$^{0.5}$)**	**Conductivity (mS/cm)**
Laboratory concrete	**>10**	**<6**	**<0.75**
Control Sample	10	10	0.2
CSFG7111	10	5.1	0.2
CSFG4114	10	6.6	0.2
CSFG4123	10	6	0.2
CSFG4132	10.4	6.23	0.1
CSFG4411	9.4	5.24	0.2
CSFG4312	9.2	5.33	0.2
CSFG4213	9.7	6.51	0.2
CSFG4141	10.5	6.92	0.2
CSFG4231	9.6	6.55	0.2
CSFG4321	9.5	7.52	0.1
CFGPD3025	9.7	7.51	0.2
CGRM5005	9.9	7.96	0.2
CS7300	9.5	5.8	0.2
CS9100	9.7	7.3	0.1
CSG5104	8.7	9.6	0.1

In general, although there is an increase of permeability at 90 days for few mixes, there is an appreciable decrease of permeability for majority of the blended concretes. This is because the addition of SCMs has been found generally to be an effective way to decrease permeability of concrete (Mehta et al. 2006; Neville et al. 2004). Figure 4.11 shows the coefficient of permeability in relation to control sample. Reduction in permeability was observed for samples CSFG7111, CSFG4114, CSFG4123, CSFG4132, CSFG4141, CGRM5005 at 28 days, with CSFG4141 having the highest reduction value (73%). It is interesting to note that in all these mixes SF has 10% content and none in CGRM5005. Other samples with higher SF content show increased in permeability than control sample. At 90 days, more blended samples show decrease in permeability compared to control sample. These additional samples are CSFG4213, CSFG4231, and CFGPD3025. In general, the combination of SF, FA, and GGBS in the mix help to reduce permeability at the instance of lower SF content. CSFG7111 and CSFG4123 show increase in permeability at 90 days compare to control sample. This trend is the opposite of what was observed at 28 days where reduction in permeability was recorded. From the Table 4.3, it can be concluded that CSFG4132, CSFG4141 & CSFG7111 samples give greater indication of better durability performance.

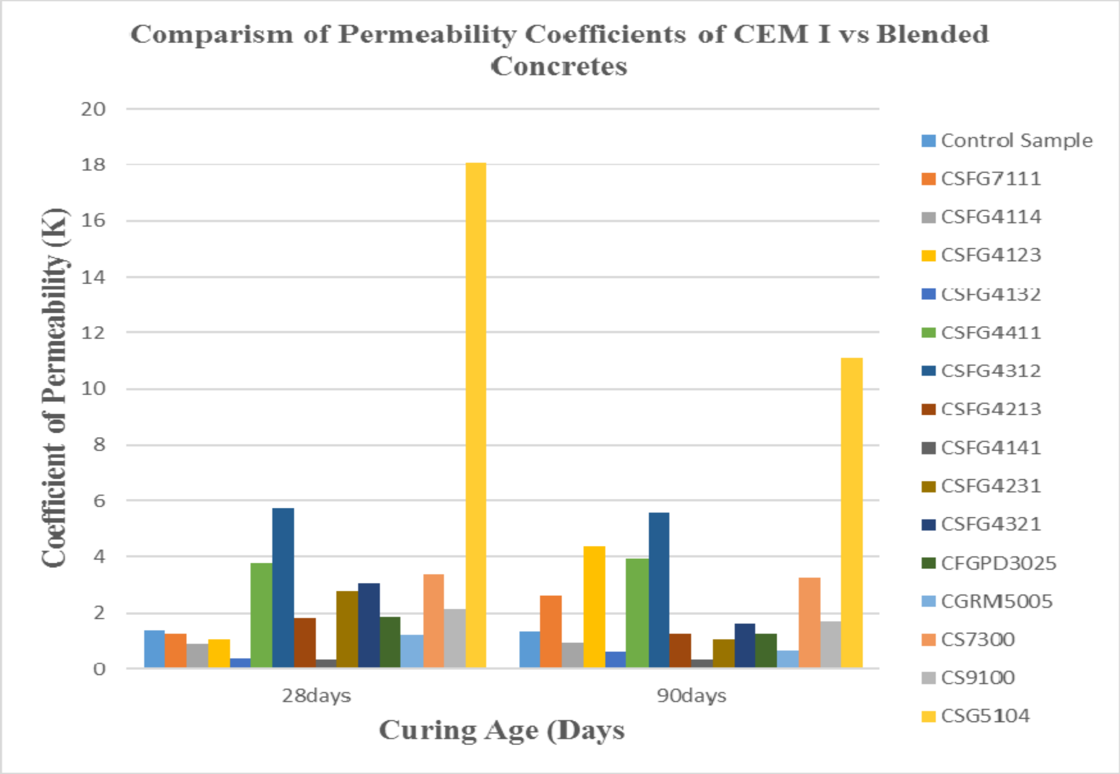


Figure 4.11: Comparison of Permeability Coefficients of CEM I vs Blended Concretes

4.5.2 Influence of blended concrete on sorptivity

The results of sorptivity test for concrete samples under investigation presented in Figures 4.12 shows the mean values of sorptivity for concretes samples tested after 28 and 90 curing days respectively. The results indicated that the sorptivity of CSG5104 (ternary) is higher than the average sorptivity of mixes containing 60% cement replacement relative to the control sample. The effect of combined use of silica fume at 10% and GGBS at 40% with 50% OPC on reducing the water absorption and sorptivity is much slightly higher than using GGBS at 50% with 50% OPC replacement.

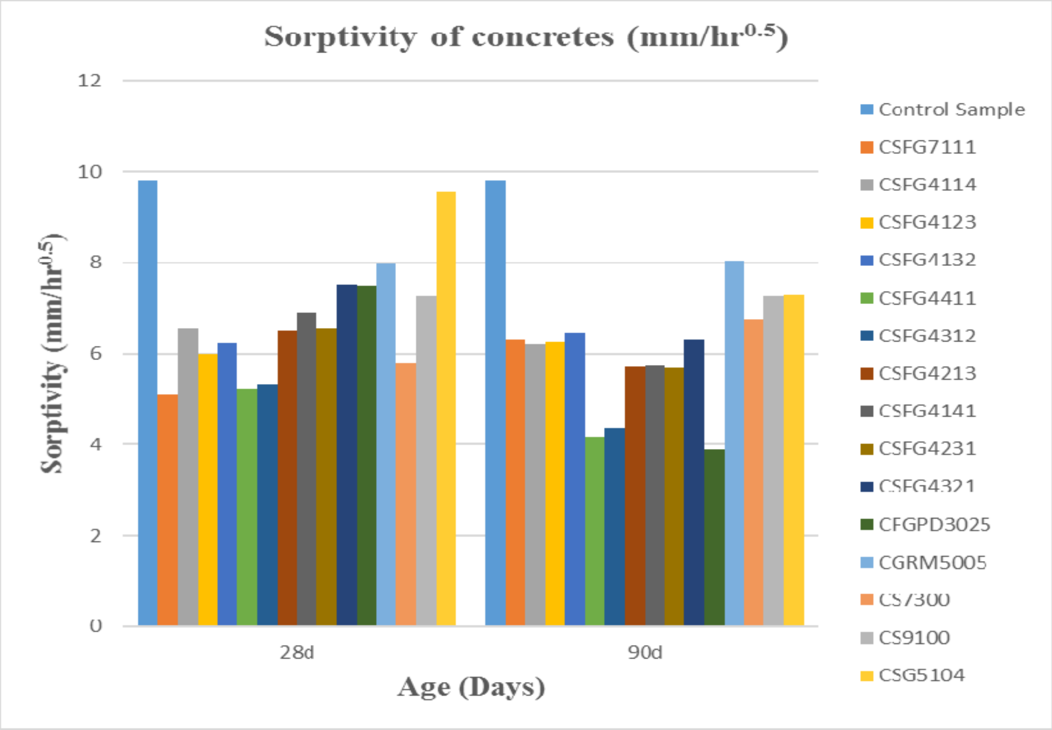


Figure 4.12: Sorptivity of concrete samples

he sorptivity value for control sample were higher than any other mixes for both 28, and 90, days respectively. The soprtivity at 28, and 90 curing days of most of the mixes are consistent with the outcome of Tasdemir et al 2003 work, which revealed that sorptivity coefficient decreased as the compressive strength of concrete increased as indicated in Table 4.2

The combination of 30%SF+20%FA+10%GGBS (CSFG4321) produced the highest sorptivity coefficient at 28 days relative to the control but there is a reverse of this performance with a combination of 10%SF+30%FA+20%GGBS (CSFG4132) at 90 days while maintaining the cement replacement at 60%. Most of the concrete samples under investigation indicate lower sorptivity values compared to the control sample at both 28 and 90 days respectively. This lower value indicate the quality of concrete cover (Angelucci et al. 2013), which is also related to the quality of the concrete.

In general, all the binary, ternary, and quaternary mixes outperformed the control sample with 100%OPC as far as sorptivity is concerned. Leung et al. 2016 suggested a further investigation on sorptivity as one of the main durability consideration, these results attempt to present some sorptivity test data on concrete containing partial replacement of OPC with SCMs at various proportion.

Conclusively, majority of the results obtained from this test does agree with Kubissa et al. 2016, who indicated that sorptivity measured for young concrete is the highest sorptivity value for given concrete. It could also be inferred that the grade of the concrete samples under investigation could be classified as between Grade 30 – 50 MPa as Alexander et al., 2004 indicated that sorptivity values typically vary from approximately 5 mm/hr$^{0.5}$ for well cured Grade 30-50 concretes, to 15 – 20 mm/hr$^{0.5}$ for poorly cured Grade 20 concrete. Figure 4.13 shows the % decrease in sorptivity for all the samples compared to the control sample. Reduction up to 48% is observed for CSFG7111 at 28 days curing period and highest reduction up to 60% is observed for CFGPD3025 at 90 days curing period. It can be concluded from Table 4.4 that CSFG4132, CSFG4141 & CSFG7111 samples give greater indication of better durability performance.

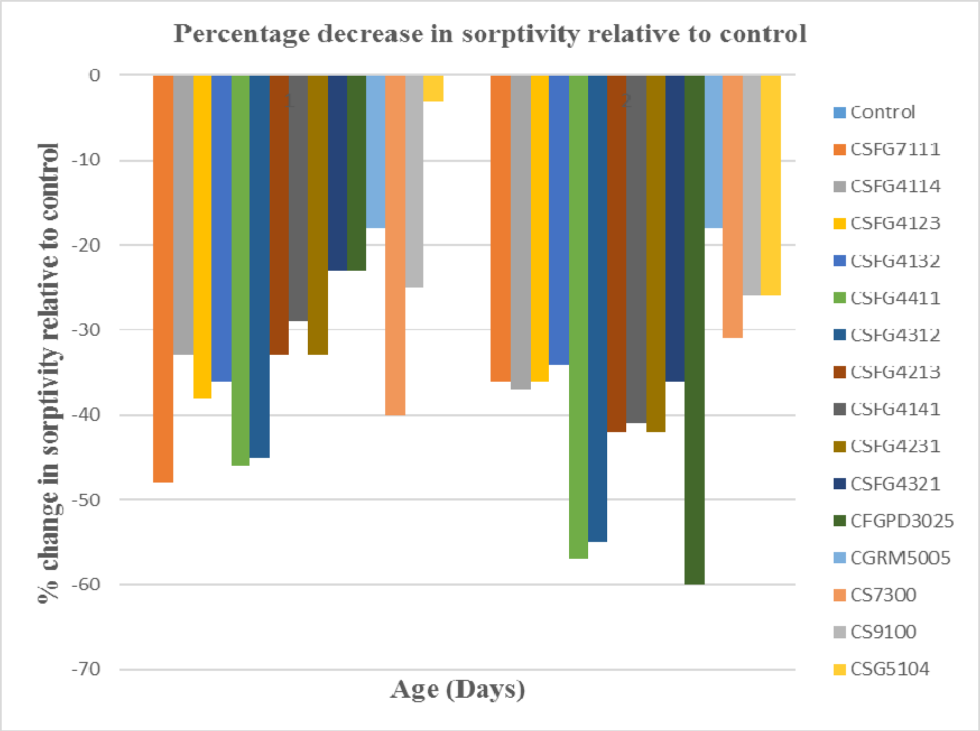


Figure 4.13: Percentage decrease in sorptivity of concrete samples relative to Control

4.5.3 Chloride conductivity of control and blended samples

Figure 4.14 shows the chloride conductivity index (CCI) of the investigated concrete samples, there is little or no difference between the obtained results for all the tested samples for both 28 and 90 days respectively. Chloride conductivity can be linked to the ingress of chlorides into the concrete (Angelucci et al. 2013). It was indicated by Angelucci et al. 2013 that CCI for concretes with similar water contents but different binder may display the same physical characteristics (same paste volume), but different chemical characteristics (different chemical proportions), which affect chloride binding capabilities. This might be responsible for little difference in the value of CCI in Figure 4.14

According to Angelucci et al. 2013, resistance to chloride conductivity provided by paste follows both physical and chemical mechanism; physical because chloride ions move by diffusion through the paste, and chemical because a portion of the ions is bound by the alluminates in the cement/binder.

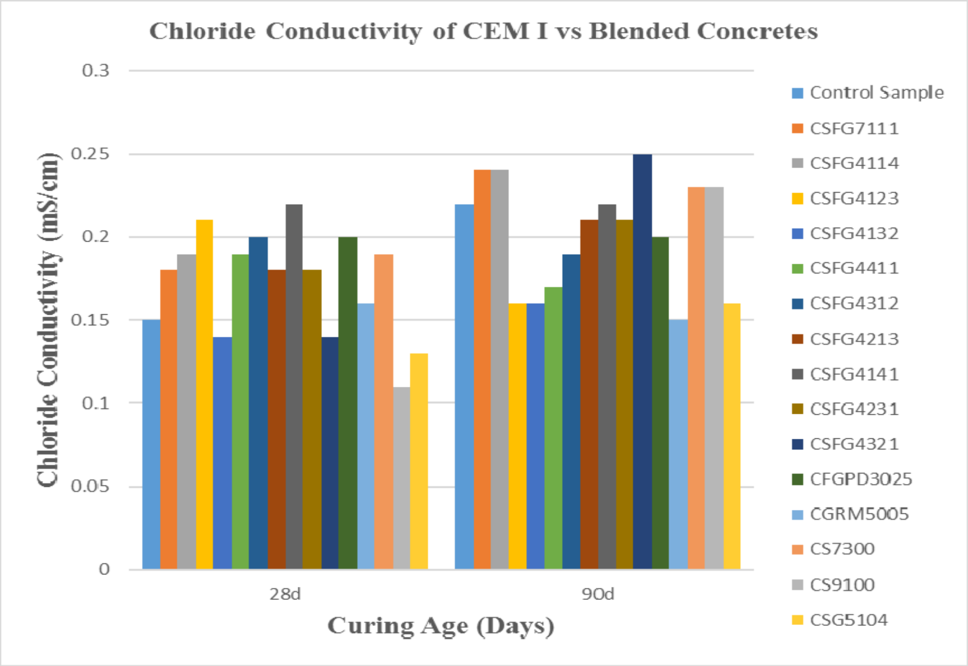


Figure 4.14: chloride conductivity index of the investigated samples

The values obtained for blended concretes follow the same pattern of relative increase from 28 to 90 days. Though some samples such as CSFG4123, CSFG4411, CSFG4312, CSFG4141, CFGPD3025, and CGRM5005 did not follow this pattern as it was expected that CCI of 28 days to be higher than that of 90 days. The enhanced chloride binding capabilities of GGBS and FA play a big role in the overall performance of the blended concretes as against the CEM I concretes as shown in Figure 4.15. The results also show that the CCI of the blended concrete increase as the fly ash increase in some quaternary mix for 28 days samples, this might be attributed to the higher amount of aluminates in the fly ash.

4.6 Electrochemical Analysis of blended concrete

4.6.1 Effect of SCM on electrode potential of a reinforced concrete in a chloride medium

Figure 4.15 (a-c) shows the relative graph of electrode potentials against the exposure time for an SCM reinforced concrete with mixed of various percentage of SCM embedded in 0.5 M solution of sodium chloride for 150 days. The electrode potential of the control sample increased slightly to less negative potential in the first 5 days as shown in the Figure 4.16 (a). This indicates that protective film was being developed on the embedded reinforced steel bar during this period, Ikotun et al 2013. On the 10th day, a decrease in electrode potential was observed; this is due to the breakdown of the protective film during the period. On further exposure for 10 days, there is an increase in electrode potential, which was due to the fact that the steel bar within the concrete was undergoing repassivation. Between 30th up to 55th days, the reinforcing steel soon de-passivated again after another 5 days, resulting in loss of protective film. This is apparent in the decrease in electrode potential from -1029.94 mV to -1030.05 mV (SCE) between 25th to 55th days of exposure. There was a slightly repassivation between 55th to 65th days exposure. However, there was a gradual decrease in electrode potential from 65th to 70th day of exposure from -1029.98 mV to -1030.07 mV (SCE). The breakdown and healing pattern of the film continued progressively towards more negative value of electrode potential.

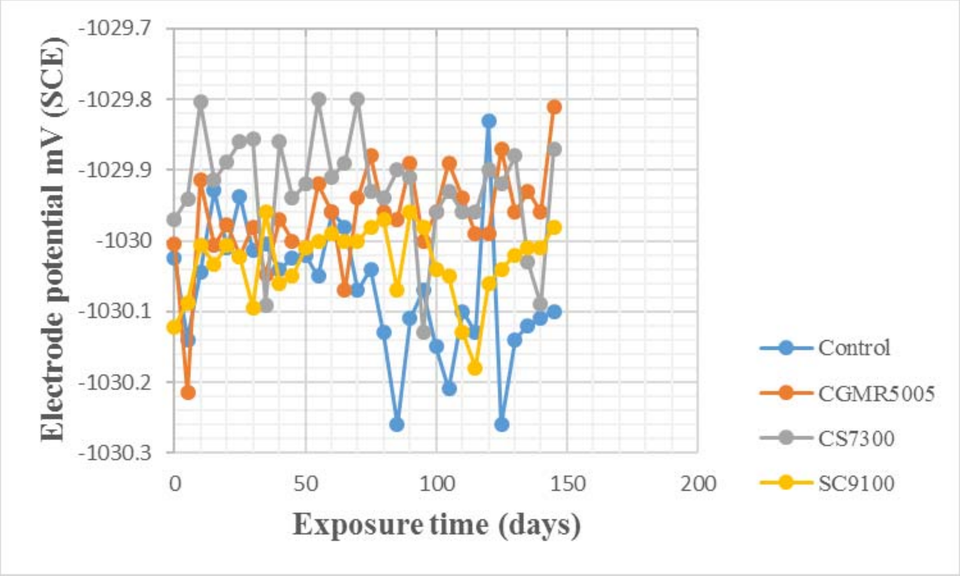


Figure 4.15a: Electrode potential vs. exposure time of SCM reinforced concrete Immersed in 0.5 M NaCl (binary combination)

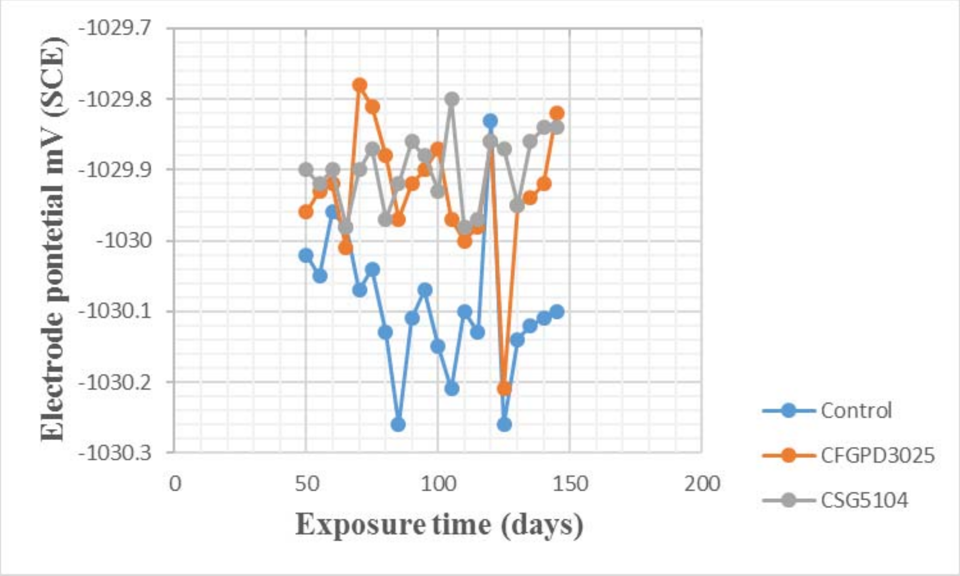


Figure 4.15b: Electrode potential vs. exposure time of SCM reinforced concrete immersed in 0.5 M NaCl (ternary combination)

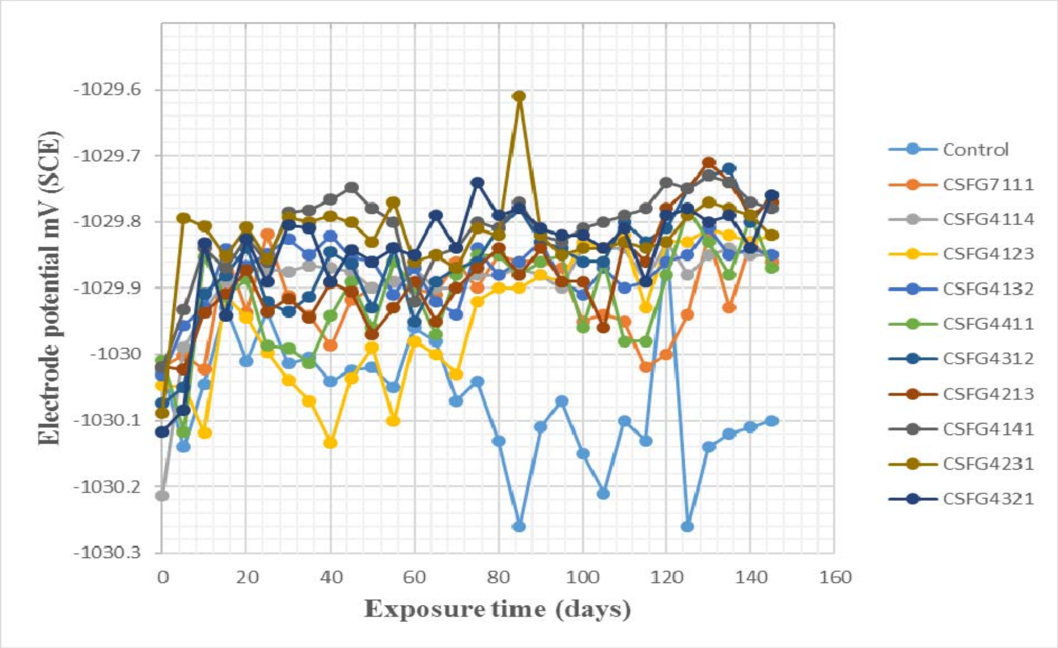


Figure 4.15c: Electrode potential vs. exposure time of SCM reinforced concrete immersed in 0.5 M NaCl (quaternary combination)

Electrochemical noise is produced due to the fluctuation of the electrode potential throughout the exposure period (Ikotun et al. 2013). This behaviour could be as a result of corrosion pits caused by chloride attacks within the crevices of the reinforcement samples in the concrete as a result of initiation and propagation of these pits (Ikotun et al. 2013). The sample mix CSFG7111 produced initial behaviour similar to the control sample from the first to 15th days of exposure after which there was development of film breakdown and healing behaviour which continued moving towards negative electrode potential values.

It is interesting to observe that from the first 5 days of exposure, the sample CSFG4114 experienced a significant increase in electrode potential from -1030.21 mV to -1029.99 mV, which was due to the fact that the embedded steel bar within the concrete was undergoing film build up. This behaviour was maintained till the end of exposure period. This could be attributed to the effect of pozzolanic reaction of SCMs within the concrete sample, Tae-Hyun Ha et al. 2007. The sample mix CSFG4123 shows no significant change in potential in the first 5 days of exposure but there was a slightly increase in electrode potential after the 10th day. A decrease in electrode potential from the 10th day to 45th day was observed, which shows behaviour of a metal undergoing film breakdown and healing started from the 40th day to the end of exposure period.

Conclusively, all the mixes exhibited similar behaviour in both solutions. However, the effect of cementitious blends is recognized in limiting the corrosion potential of the tested SCM concrete samples. The binary, ternary, and quaternary test samples show fluctuations in their electrode potentials throughout the exposure period due to the reasons already discussed earlier. These electrode potentials however gradually moved to lesser negative values, respectively.

4.6.2. Effect of SCM on electrode potential of a reinforced concrete in a sulphate medium

Figure 4.16 (a-c) shows the comparative plot of electrode potentials versus exposure time for SCM reinforced concrete mixed with various percentage of SCM (Table 3.1) in 0.5 M solution of magnesium sulphate for 150 days.

There was no significant change in the electrode potential in the first 15 days unlike the samples exposed to sodium chloride environment, which showed slight increase in electrode potential in the first 5 days of exposure. Between the 15th and 25th days, a slight increase in the electrode potential was observed, which could be due to formation of protective film on the surface of reinforcing bar during this period. There was a slightly decrease in the electrode potential from the 25th to 35th days. This behaviour is similar to that exhibited by the samples exposed to sodium chloride throughout the experiment until the 140th day whereby a stable electrode potential was seen, and it was maintained till the end of the exposure period.

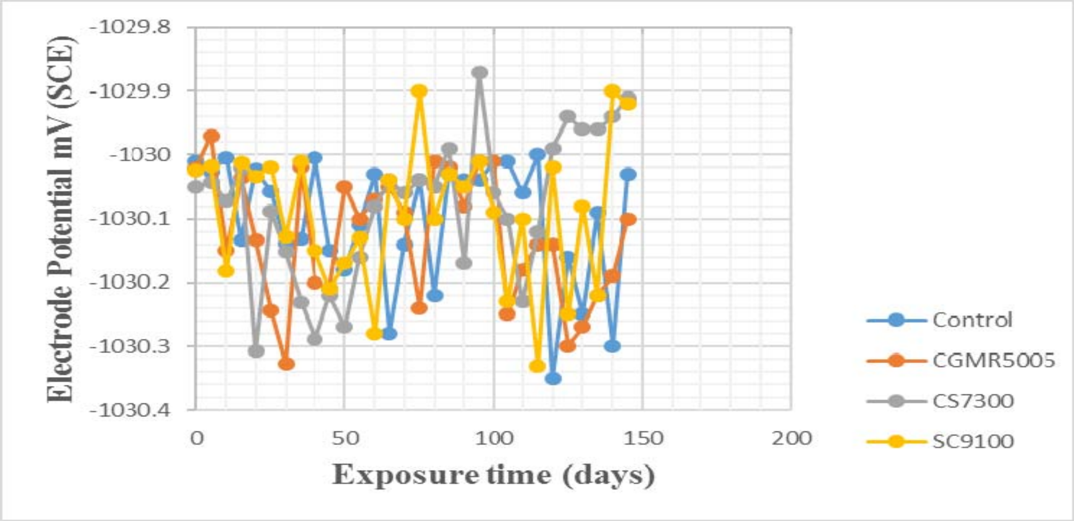


Figure: 4.16 (a) Electrode potential vs. exposure time of SCM reinforced concrete immersed in 0.5 M $MgSO_4$ (binary combination)

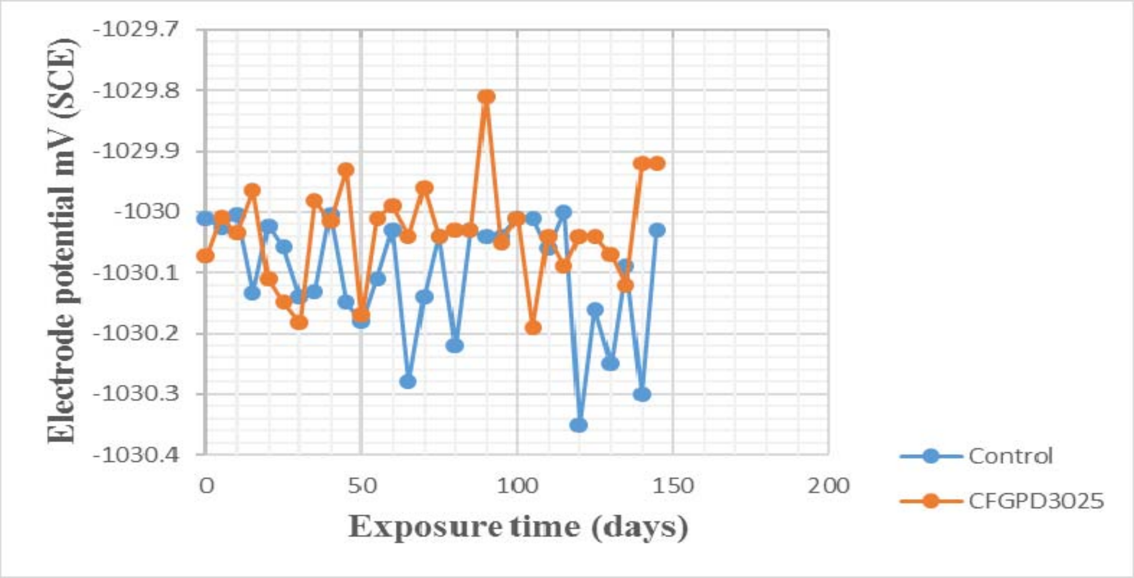


Figure 4.16 (b): Electrode potential vs. exposure time of SCM reinforced concrete immersed in 0.5M $MgSO_4$ (ternary combination)

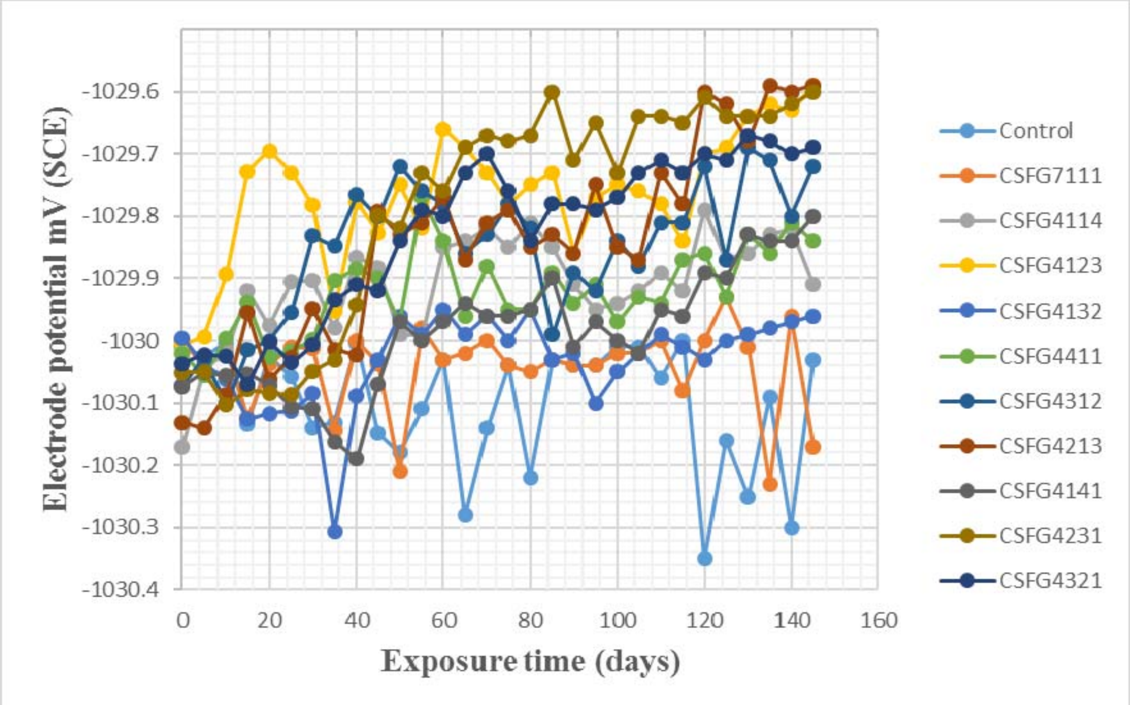


Figure 4.16 (c) Electrode potential vs. exposure time of SCM reinforced concrete immersed in 0.5M $MgSO_4$ (quaternary combination)

Unlike its behaviour in sodium chloride, sample CSFG4123 shows a significant increase in the electrode potential for the first 5 days of exposure. This increase continued till the 25th day, when a slightly decrease in the electrode potential was seen between the 25th to 35th day. However, after the 35th day, there was a similar behaviour of film breakdown and healing as experienced with the samples exposed to sodium till the 125th day which was stable till the end of exposure period.

It is interesting to note the mode of sulphate attack on samples exposed to magnesium sulphate environments. The physical examination revealed the mode of degradation common to concrete exposed to sulphate environments especially concrete with blended cements, which is similar to eating away of the hydrated cement paste and progressively reducing samples to cohesion less granular mass. This might be responsible for the loss in decrease in compressive strength observed for samples exposed to magnesium sulphate compared to samples exposed to sodium chloride environment for the same period as indicated in Table 4.4.

Table 4.4: Average test results for compressive strength of samples cured in both NaCl and $MgSO_4$ for 150days

Mix ID	Compressive strength of samples exposed to Sodium Chloride for 150 days	Compressive strength of samples exposed to Magnesium sulphate for 150 days
Control	70.77	60.67
CSFG7111	55.73	47.53
CSFG4114	49.77	37.81
CSFG4123	44.49	29.88
CSFG4132	37.60	28.82
CSFG4411	37.30	26.32
CSFG4312	36.08	26.99
CSFG4213	43.33	30.19
CSFG4141	41.84	30.11
CSFG4231	40.09	27.43
CSFG4321	37.26	29.34
CFGPD3025	36.20	29.78
CGMR5005	58.37	52.66
CS7300	47.70	44.25
SC9100	52.65	53.81
CSG5104	33.39	37.77

Further observation shows various cracks on the surface of the samples, this method of deterioration is usually categorized by expansion and cracking when the reactive hydrated aluminate present in sufficient quantities are attacked by sulphate ions, thereby forming tricalcium-sulfo-aluminate hydrate often called ettringite. The excessive expansion in concrete is generated by the formation of ettringite. However, the mechanisms by which ettringite formation causes expansion is still a subject of controversy as alluded to by Baghara et al. 2002. The most prominent observed mode of sulphate attack among the samples exposed to magnesium sulphate was the scaling of the surface in successive layers in the form of delamination as reported by Figg et al. 1979. It was reported by Al-Amoudi et al. 1992 that concretes incorporating pozzolanic materials and low water to binder generate a very fine pore structure that cannot accommodate the build-up of salt crystals. The formation of these salt crystals in the fine pore structure of pozzolanic concrete exerts considerable pressure, resulting in greater expansion and deterioration of concrete. The outcome of this degradation may lead to formation of scaling which was evident on the blended concretes as against the control sample.

4.6.3. Weight loss measurements

Figure 4.17 and 4.18 illustrate the relationships between weight loss and immersion time. The results compared the weight loss of the reinforcement samples exposed to both sodium chloride and magnesium sulphate environment, respectively. The weight loss of control samples exposed to sodium chloride and magnesium sulphate media show the same pattern of corrosion rate except that there is a breakdown of passivity of samples exposed to magnesium sulphate towards the end of the exposure period.

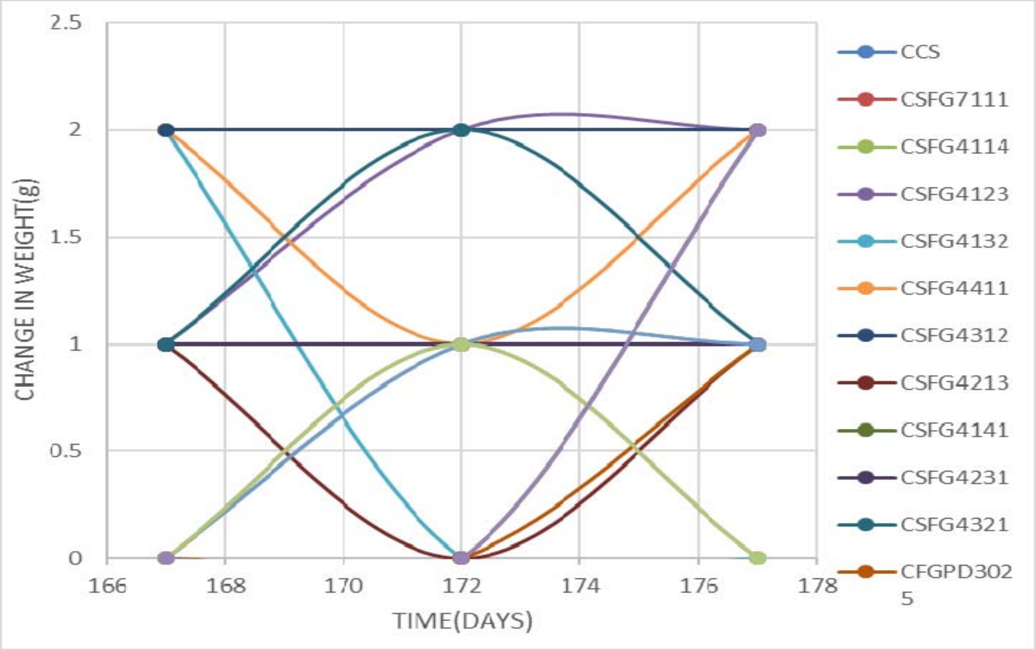


Figure 4.17: Change in weight over time of reinforcement embedded in sodium chloride concrete

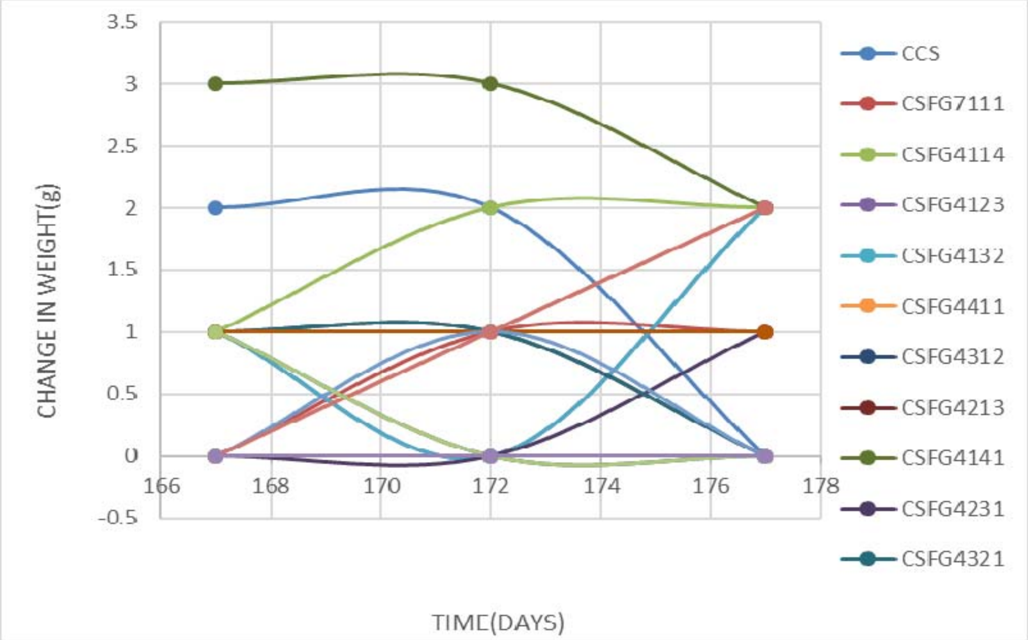


Figure 4.18: Change in weight over time of reinforcement embedded in magnesium sulphate concrete

In the Table 4.5, CSFG4114 exposed to sodium chloride shows that for the first five days of exposure, there is an initial increase in weight loss, this shows that there was a rapid corrosion taking place, but between the next five days, there is a reduction in the weight loss, this indicates passivity which led to lower corrosion rate. On the contrary, the same mix exposed to magnesium sulphate shows a steady increase in weight loss for the first five days of exposure which became stable with increase in time of exposure; this also led to an increase in corrosion rate as illustrated in Table 4.5.

Table 4.5: Weight loss measurements for both Sodium Chloride& Magnesium Sulphate

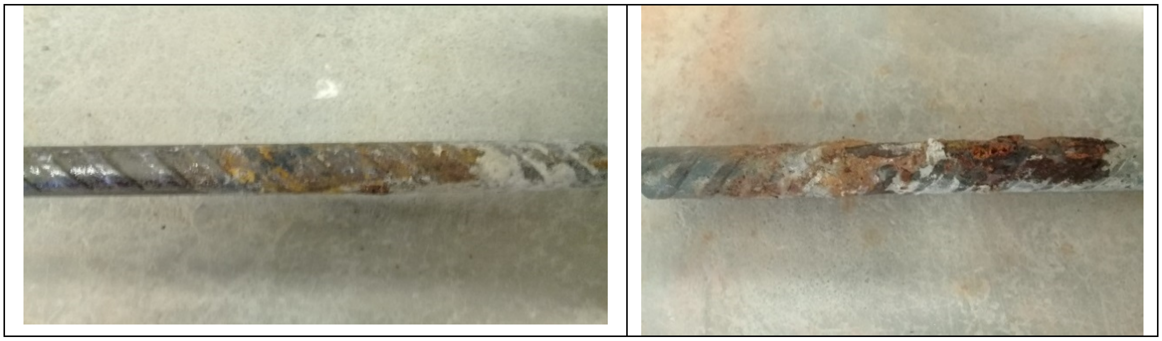
MIX ID	sodium chloride measurements		Magnesium sulphate measurements	
	Time (Days)	corrosion rate mm/yr	Time (Days)	corrosion rate mm/yr
CCS	167	0.108423	167	0.108423
	172	0.105272	172	0.105272
	177	0.102298	177	0
CSFG7111	167	0.054212	167	0
	172	0.052636	172	0.052636
	177	0.051149	177	0.051149
CSFG4114	167	0	167	0.054211736
	172	0.052636	172	0.105272
	177	0.051149	177	0.102298
CSFG4123	167	0.054212	167	0.054212
	172	0.105272	172	0
	177	0.102298	177	0.102298
CSFG4141	167	0		0.162635
	172	0		0.157907
	177	0.102298		0.102298
CGMR5005	167	0	167	0
	172	0.052636	172	0.052636
	177	0.051149	177	0

CSFG4141 exposed to sodium chloride shows that there is no change from the initial exposure period of the first five days, this indicate the possibility of stable oxide film formed on the surface of the reinforcement. However, this is contrary to the same sample exposure to magnesium environment which shows a steady passivation from the beginning of exposure to the medium. Although it has the highest corrosion rate compared to other specimens, yet it showed a steady decrease in weight loss. This could be attributed to formation of unstable passive layers on the surface of the specimen. Similar behaviour was observed on the control sample exposed to magnesium sulphate environment. It was also observed that CSFG4141 exposed to magnesium sulphate has the highest corrosion rate of 0.16 mm/yr. However, in sodium chloride, the corrosion rate was 0.10 mm/yr. This indicates that the sample corroded more in the magnesium sulphate than in sodium chloride environment.

The physical observations on the corroded samples showed that the corroded area is mostly the interface between the concrete and the area exposed to the environment. The areas were between 25 mm to 60 mm from the interface to the outer top of the reinforcement. The longest corrosion length of 95 mm which occurred from the outer face into the concrete was observed on sample CSFG7111 exposed to sodium chloride environment as shown in Figure 4.19 – 4.20.

CCS_NaCl CSFG7111_NaCl

Figure 4.19: physical observations of reinforced concrete samples cured in Sodium Chloride



CSFG4213_NaCl CSFG7111_NaCl

Figure 4.20: Corroded coupons embedded in the concrete cured in Sodium Chloride

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, the effect of South African supplementary cementitious blends on corrosion behaviour of concrete reinforcement in chloride and sulphate media was investigated. Three cementitious materials: fly ash, silica fume, and ground granulated blast furnace were combined with Ordinary Portland Cement (OPC) in various proportions. As a control, a concrete sample was prepared with 100% OPC. Properties of the control samples were evaluated and compared to the corresponding properties of samples in which SCMs were used. The properties of concretes that were evaluated included workability, compressive strength, resistance to both chloride and sulphate attack, oxygen permeability, sorptivity, and porosity. Half-cell methodology was employed to determine the electrode potentials of the tested samples. Based on observations and trends determined from the results of this evaluation, the followings conclusions were made:

1. The workability test showed that percentage inclusion of various extenders played a big role in the workability performance of the sample mixes. The results showed an improvement of workability as the GGBS increases, while there was reduction of workability as SF increases. The higher the percentage of SF content, the stickier the sample, hence reduction of the samples workability.

2. It was found that the higher the curing days, the lower the rate of strength increase. At the early ages, both binary, ternary, and quaternary blended samples showed slightly lower strength than the corresponding control sample made with 100% OPC. With increase in age, the pozzolanic reaction of the blended cements increases and consequently rate of strength increases for all mixes for 7 days over 14 days samples ranges from 60% - 85% compared to control sample which stands at 99%

3. The compressive strength results showed that the compressive strength increases as the age increases for most of the samples but interestingly, there is a 3%, 2%, and 1% strength decrease for control sample and CSFG4411, and CSG5104 respectively after 90 curing days.

4. The combination of 30%SF, 20%FA and 10%GGBS (CSFG4321) produced 24.40 MPa which is 43.4% of the control sample at 7 curing days. However, the combination of 10%SF, 20%FA and 30%GGBS (CSFG4123) produced the highest strength of 41.12MPa at 28 days which is 69% of the control sample at that age.

5. The binary combination CS9100 (Mix 15) and quaternary combination of CSFG7111 (Mix 2) produced the highest strength of 67.87MPa and 60.8MPa respectively among the blended samples at 120 days as against control sample of 68.3MPa maintained at 100% OPC at the same curing age.

6. The results showed that the sample with 10% each of SCMs in the mix (CSFG7111) showed increase in strength at a desired rate compared to the control sample. This sample CSFG7111 showed 54% strength of control sample at 7 days and 89% strength of the control sample at 120 days.

7. The compressive strength results of samples cured in aggressive media showed that the sulphate attack has greater adverse effect on concrete after long exposure of 150 days than sodium chloride attack. Interestingly, a comparison of the results showed that all samples cured in sodium chloride have higher strength than samples cured in sulphate medium. There was an exception of binary sample CS9100 and ternary sample CS5104 cured in magnesium sulphate which gained more strength by 1.16 MPa (1.08%) and 4.38 MPa (6.16%) respectively over samples cured in sodium chloride.

8. Reduction in permeability was observed for samples CSFG7111, CSFG4114, CSFG4123, CSFG4132, CSFG4141 and CGRM5005 at 28 days with CSFG4141 having the highest reduction value of 73%. However, it is interesting to note that in all mixes

mentioned above, SF has 10% content except CGRM5005. Other samples with higher SF content showed increased in permeability than control sample. At 90 days, samples CSFG4213, CSFG4231, and CFGPD3025 showed decrease in permeability compared to control sample.

9. In general, combination of SF, FA, and GGBS in the mix assisted in reducing permeability at the instance of lower SF content. Samples CSFG7111 and CSFG4123 showed increase in permeability at 90 days compared to control sample. This trend was the opposite of what was observed at 28 days where reduction in permeability was recorded.

10. The sorptivity value for control sample were higher than any other samples for both 28 and 90 days respectively. It was also found that the sorptivity of CSG5104 (ternary) was higher than the average sorptivity of samples containing 60% cement replacement relative to the control sample.

11. The effect of combined use of SF at 10% and GGBS at 40% with 50% OPC on reducing the water absorption and sorptivity was much slightly higher than using GGBS at 50% with 50% OPC replacement.

12. The combination of 30%SF+20%FA+10%GGBS (CSFG4321) produced the highest sorptivity coefficient at 20 days relative to the control but there is a reverse of this performance with a combination of 10%SF+30%FA+20%GGBS (CSFG4132) at 90 days while maintaining the cement replacement at 60%.

13. In general, all the binary, ternary, and quaternary mixes outperformed the control sample with 100%OPC as far as sorptivity is concerned.

14. The values obtained for blended concretes follows the same pattern of relative increase from 28 to 90 days. Though some samples such as CSFG4123, CSFG4411, CSFG4312,

CSFG4141, CFGPD3025, and CGRM5005 did not follow this pattern as it was expected that CCI of 28 days to be higher than that of 90 days.

15. The physical observations on the corroded samples show that the corroded area is mostly the interface between the concrete and the area exposed to the environment. The areas were between 25 mm to 60 mm from the interface to the outer top of the reinforcement. The longest corrosion length of 95 mm which occurred from the outer face into the concrete was observed on sample CSFG7111 exposed to sodium chloride environment.

16. Conclusively, all the mixes exhibited similar behaviour in both solutions. However, the effect of cementitious blends is recognized in limiting the corrosion potential of the tested SCM concrete samples. Both the binary, ternary, and quaternary test samples show variability in their electrode potentials throughout the exposure.

5.2 Recommendations

1. Further tests should be performed on quaternary combination of CSFG7111, CSFG4123, CSFG4321. Interest on this samples was based on the better performance they have over the mechanical properties of concrete when compared with the control sample. However, such trend was not observed for durability and corrosion tests. These should be compared to quaternary combination of CSFG4141, which gives the best improved permeability.
2. Further durability index tests (sulphate attack and alkali silica reaction) should be performed on the samples.
3. Generally, the cementitious blends with limited quantity of SF to 10% have the potential to produce satisfactory concrete. These should however be used for low cost construction, where high quality concrete is not required.

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APPENDIX A : DETAILED EXPERIMENTAL RESULTS

Table A-1 : Tests matrix of phase 1(Concrete)

W/B	0.5	0.5	0.5	0.5	0.5
	Tests				
Sample	Compressive strength	Workability (Slump)	Oxygen permeability	Sorptivity	Chloride conductivity
CCS	X	X	X	X	X
CSFG7111	X	X	X	X	X
CSFG4114	X	X	X	X	X
CSFG4123	X	X	X	X	X
CSFG4132	X	X	X	X	X
CSFG4411	X	X	X	X	X
CSFG4312	X	X	X	X	X
CSFG4213	X	X	X	X	X
CSFG4141	X	X	X	X	X
CSFG4231	X	X	X	X	X
CSFG4321	X	X	X	X	X
CFGPD3025	X	X	X	X	X
CGMR5005	X	X	X	X	X
CS7300	X	X	X	X	X
SC9100	X	X	X	X	X
CSG5104	X	X	X	X	X

Table A-2: Particle Shape (Flakiness)

Sieve (mm)	Flakiness (g)	Non-Flakiness (g)	% Flakiness TMH1 B3T
26.5	-	57.4	% Flakiness = $\frac{\text{Flakiness}}{\text{Total}} \times 100$ $= \frac{420.6}{2618.8} \times 100 = 16.06\%$ It is recommended for concreting
19.0	103.0	1032.7	
13.2	299.4	1054.5	
9.5	17.8	52.7	
6.7	0.4	0.5	
4.75	-	0.4	
Sub-total	420.6	2198.2	
Total	2618.8		

Table A-3: Sieve Analysis Test Result

SAND	1	2	3	4	5	6	
Total Mass 617.1g	Sieve Unit (mm)	Individual Mass Retained R	Individual % retained (R/total x 100)	Cumulative % 4750-150) sieves	% of material that passed	% of material that passed (rounded off)	FM = $\frac{4.75 - 0.150}{100}$ = 367.8/100 = 3.68
	6.7	0.6	0.1	0.1	99.9	100	
	4.75	49.8	8.1	8.2	91.8	92	
	2.36	227.8	36.9	45.1	54.9	55	
	1.18	127.9	20.7	65.8	34.2	34	
	0.6	68.9	11.2	77.0	23.0	23	
	0.3	41.4	6.7	83.7	16.3	16	
	0.15	26.6	4.3	88	12.0	12	
	0.075	18.1	2.9		9.1	9.1	
STONE	1	2	3	4	5	6	
Total Mass 2624.5g	Sieve (mm)	Individual Mass Retained R	Individual % retained (R/total x 100)	Cumulative % 4750-150) sieves	% of material that passed	% of material that passed (rounded off)	
	26.5	57.6	2.2	2.2	97.8	98	
	19.0	1135.6	43.3	45.5	54.5	55	
	13.2	1353.8	51.6	97.1	2.9	3	
	9.5	70.5	2.7	99.8	0.2	0	
	6.7	0.9	0.0	99.8	0.2	0	
	4.75	0.4	0.0	99.8	0.2	0	
	2.36	0.5	0.0	99.8	0.2	0	
	1.18	0.3	0.0	99.8	0.2	0	
	0.6	0.2	0.0	99.8	0.2	0	
	0.3	0.2	0.0	99.8	0.2	0	
	0.15	0.4	0.0	99.8	0.2	0	
	0.075	0.5	0.0	99.8	0.2	0	

Table A-4: Cubes identification for compressive and durability series

Mix No.	Mix ID	Cement %	SF %	FA %	GGBS %	Reference Number	Reference Number	Compressive strength @ 7,14,28 & 90, 120 days (Cubes tested)	Durability @ 28,90,120 (days) (Cubes tested)	Total no of cubes
1	CCS	100	-	-	-	CCS001-18	CBS001-6	15	12	27
2	CSFG7111	70	10	10	10	CSFB7111 (1-18)	BSFG4111 (1-6)	15	12	27
3	CSFG4114	40	10	10	40	CSFG7114 (1-18)	BSFG4114 (1-6)	15	12	27
4	CSFG4123	40	10	20	30	CSFG4123 (1-18)	BSFG4123 (1-6)	15	12	27
5	CSFG4132	40	10	30	20	CSFG4132 (1-18)	BSFG4132 (1-6)	15	12	27
6	CSFG4411	40	40	10	10	CSFG4411 (1-18)	BSFG4411 (1-6)	15	12	27
7	CSFG4312	40	30	10	20	CSFG4312 (1-18)	BSFG4312 (1-6)	15	12	27
8	CSFG4213	40	20	10	30	CSFG4213 (1-18)	BSFG4213 (1-6)	15	12	27
9	CSFG4141	40	10	40	10	CSFG4141 (1-18)	BSFG141 (1-6)	15	12	27
10	CSFG4231	40	20	30	10	CSFG4231 (1-18)	BSFG231 (1-6)	15	12	27
11	CSFG4321	40	30	20	10	CSFG4321 (1-18)	BSFG321 (1-6)	15	12	27
12	CFGPD3025*	30	-	20	50	CFGPD3025	BFG325	15	12	27
13	CGRMR5005*	50	-	-	50	CGMR5005	BG55	15	12	27
14	CS7300*	70	30	-	-	CS7300	BS3	15	12	27
15	CS9100*	90	10	-	-	CS9100	BF3	15	12	27
16	CSG5104*	50	10	-	40	CSG5104	BG3	15	12	27

CCS = Control Cube Sample; CBS = Control Beam Sample; CSG = Cement Silica GGBS; CS7300* = Berry & Molhotra work and SA
CSFG = Cement Silica Fume Fly Ash GGBS; CFGPD3025* = P.Dinakar et al 2006 work; CS9100* = SA works
BSFG = Beam Silica Fume Fly Ash GGBS; CGMR5005* = Meusel & Ros work and SA; CSG5104* = SA Work

Table A-5: Mix Design for compressive and durability series

No.	Mix ID	Date Cast	Actual Slump (mm)	Cement % composition				Cement Content (kg/m^3)				Water Content (kg/m^3)	Fine agg content (kg/m^3)	Coarse agg content (kg/m^3)
				OPC	SF	FA	GGBS	OPC	SF	FA	GGBS			
1	CCS	19-10-16	33	100	-	-	-	420	-	-	-	210	824.66	1091
2	CSFG7111	24-11-16	50	70	10	10	10	294	42	42	42	210	824.66	1091
3	CSFG4114	29-11-16	49	40	10	10	40	168	42	42	168	210	824.66	1091
4	CSFG4123	30-11-16	67	40	10	20	30	168	42	84	126	210	824.66	1091
5	CSFG4132	15-12-16	68	40	10	30	20	168	42	126	84	210	824.66	1091
6	CSFG4411	20-12-16	35	40	40	10	10	168	168	42	42	210	824.66	1091
7	CSFG4312	22-12-16	62	40	30	10	20	168	126	42	84	210	824.66	1091
8	CSFG4213	23-12-16	67	40	20	10	30	168	84	42	126	210	824.66	1091
9	CSFG4141	24-12-16	63	40	10	40	10	168	42	168	42	210	824.66	1091
10	CSFG4231	27-12-16	56	40	20	30	10	168	84	126	42	210	824.66	1091
11	CSFG4321	28-12-16	35	40	30	20	10	168	126	84	42	210	824.66	1091
12	CFGPD3025*	25-10-16	65	30	-	20	50	126	-	84	210	210	824.66	1091
13	CGRMR5005*	27-10-16	49	50	-	-	50	210	-	-	210	210	824.66	1091
14	CS7300*	29-12-16	20	70	30	-	-	294	126	-	-	210	824.66	1091
15	CS9100*	30-12-16	20	90	10	-	-	378	42	-	-	210	824.66	1091
16	CSG5104*	31-12-16	57	50	10	-	40	120	42	-	168	210	824.66	1091

Table A-6: Mix Design for corrosion series

No.	Mix ID	Cement % composition				Cement Content (kg/m^3)				Water Content (kg/m^3)	Fine agg content (kg/m^3)	Coarse agg content (kg/m^3)
		OPC	SF	FA	GGBS	OPC	SF	FA	GGBS			
1	CCS	100	-	-	-	420	-	-	-	210	824.66	1091
2	CSFG7111	70	10	10	10	294	42	42	42	210	824.66	1091
3	CSFG4114	40	10	10	40	168	42	42	168	210	824.66	1091
4	CSFG4123	40	10	20	30	168	42	84	126	210	824.66	1091
5	CSFG4132	40	10	30	20	168	42	126	84	210	824.66	1091
6	CSFG4411	40	40	10	10	168	168	42	42	210	824.66	1091
7	CSFG4312	40	30	10	20	168	126	42	84	210	824.66	1091
8	CSFG4213	40	20	10	30	168	84	42	126	210	824.66	1091
9	CSFG4141	40	10	40	10	168	42	168	42	210	824.66	1091
10	CSFG4231	40	20	30	10	168	84	126	42	210	824.66	1091
11	CSFG4321	40	30	20	10	168	126	84	42	210	824.66	1091
12	CFGPD3025*	30	-	20	50	126	-	84	210	210	824.66	1091
13	CGRMR5005*	50	-	-	50	210	-	-	210	210	824.66	1091
14	CS7300*	70	30	-	-	294	126	-	-	210	824.66	1091
15	CS9100*	90	10	-	-	378	42	-	-	210	824.66	1091
16	CSG5104*	50	10	-	40	120	42	-	168	210	824.66	1091

Table A-7: Total Quantities of materials for corrosion series

No.	Mix ID	Cement % composition				cement content (g)				Water Content (g)	Fine agg content (g)	Coarse agg content (g)	Reinforcement Y12 (m)
		OPC	SF	FA	GGBS	OPC	SF	FA	GGBS				
1	CCS	100	-	-	-	10080	-	-	-	5040	26184	19792	0.17
2	CSFG7111	70	10	10	10	7056	1008	1008	1008	5040	26184	19792	0.17
3	CSFG4114	40	10	10	40	4032	1008	1008	4032	5040	26184	19792	0.17
4	CSFG4123	40	10	20	30	4032	1008	2016	3024	5040	26184	19792	0.17
5	CSFG4132	40	10	30	20	4032	1008	3024	2016	5040	26184	19792	0.17
6	CSFG4411	40	40	10	10	4032	4032	1008	1008	5040	26184	19792	0.17
7	CSFG4312	40	30	10	20	4032	3024	1008	2016	5040	26184	19792	0.17
8	CSFG4213	40	20	10	30	4032	2016	1008	3024	5040	26184	19792	0.17
9	CSFG4141	40	10	40	10	4032	1008	4032	1008	5040	26184	19792	0.17
10	CSFG4231	40	20	30	10	4032	2016	3024	1008	5040	26184	19792	0.17
11	CSFG4321	40	30	20	10	4032	3024	2016	1008	5040	26184	19792	0.17
12	CFGPD3025*	30	-	20	50	3024	0	2016	5040	5040	26184	19792	0.17
13	CGRMR5005*	50	-	-	50	5040	0	0	5040	5040	26184	19792	0.17
14	CS7300*	70	30	-	-	7056	3024	0	0	5040	26184	19792	0.17
15	CS9100*	90	10	-	-	9072	1008	0	0	5040	26184	19792	0.17
16	CSG5104*	50	10	-	40	2880	1008	0	4032	5040	26184	19792	0.17

Table A-8: Compressive Strength Test Results

Mix	Mass kg	7days MPa	Ave	Mass kg	14days Mpa	Av	Mass kg	28days Mpa	Ave	Mass kg	90days Mpa	Av	Mass kg	120days Mpa	Av
CCSa	8.53	57.60	56.19	8.55	57.52	57.02	8.62	59.80	60.05	8.70	68.38	70.59	8.7	67.24	68.30
b	8.63	55.83		8.59	57.69		8.55	60.55		8.69	73.80		8.7	65.06	
c	8.62	55.15		8.66	55.84		8.63	59.81		8.68	69.59		8.6	72.50	
CSFG7111a	8.30	29.25	30.12	8.34	42.58	43.37	8.32	53.80	49.95	8.34	58.38	55.83	8.4	59.35	60.89
b	8.29	29.03		8.24	43.91		8.27	48.56		8.32	55.03		8.4	59.56	
c	8.37	32.08		8.36	43.62		8.25	47.48		8.30	54.07		8.4	63.77	
CSFG4114a	8.25	20.70	20.89	8.15	31.05	30.95	8.24	37.77	37.26	8.22	53.15	52.00	8.3	52.48	52.02
b	8.30	21.08		8.26	31.24		8.12	37.13		8.30	50.42		8.3	53.54	
c	8.10	20.88		8.17	30.56		8.07	36.87		8.24	52.41		8.2	50.05	
CSFG4123a	8.38	21.67	20.20	8.33	33.38	31.24	8.35	41.24	41.12	8.41	51.34	48.88	8.4	57.25	56.13
b	8.34	20.74		8.31	32.52		8.42	41.68		8.42	52.51		8.4	55.48	
c	8.22	18.19		8.17	27.81		8.37	40.43		8.31	42.78		8.4	55.66	
CSFG4132a	8.20	16.79	17.46	8.30	29.86	28.94	8.24	35.53	36.75	8.30	48.93	45.87	8.2	52.03	52.22
b	8.28	18.41		8.25	28.15		8.21	36.87		8.31	42.25		8.2	51.63	
c	8.13	17.18		8.25	28.81		8.33	37.84		8.13	46.43		8.3	53.01	
CSFG4411a	7.88	20.97	20.56	7.85	29.85	29.46	7.87	34.60	32.20	7.97	45.23	48.25	7.9	47.75	47.23
b	7.85	20.10		7.70	27.84		7.84	31.31		7.99	47.50		7.8	43.48	
c	7.84	20.60		7.79	30.68		7.78	30.68		8.01	52.01		8.0	50.45	
CSFG4312a	7.88	17.81	16.75	7.96	28.96	27.82	8.08	37.24	38.29	7.94	47.24	44.71	7.8	44.78	45.72
b	7.82	17.49		8.06	29.82		7.96	37.45		7.83	44.80		7.8	44.78	
c	7.64	14.96		7.75	24.82		8.06	40.18		7.78	42.10		8.0	47.59	
CSFG4213a	8.24	19.58	19.10	8.16	31.95	29.90	8.1	34.73	36.90	8.1	48.78	50.09	8.2	52.16	54.69
b	8.11	18.19		8.15	29.59		8.1	38.64		8.0	51.74		8.2	55.15	
c	8.23	19.51		7.98	28.15		8.1	37.32		8.0	49.76		8.1	56.75	
CSFG4141a	8.14	17.14	16.22	8.15	25.37	26.07	8.1	32.84	35.14	8.2	49.69	47.57	8.3	51.57	48.95
b	8.29	16.85		8.16	27.49		8.3	37.76		8.2	47.13		8.2	48.35	
c	8.03	14.67		8.03	25.36		8.1	34.81		8.1	45.89		8.2	46.92	
CSFG4231a	8.10	18.23	18.11	8.02	28.65	26.29	8.0	35.16	33.04	7.9	43.17	42.68	8.1	44.64	42.86
b	7.82	16.96		7.92	25.34		7.9	30.80		7.8	39.42		7.9	38.93	
c	8.03	18.11		7.85	24.88		7.9	33.15		8.1	45.46		8.1	45.00	
CSFG4321a	8.22	24.46	24.40	8.16	34.54	35.30	8.2	39.92	39.75	8.4	55.98	52.69	8.1	50.27	50.06
b	8.16	24.58		8.31	36.40		8.1	40.24		8.2	52.92		8.0	51.80	
c	8.19	24.17		8.25	34.97		8.0	39.10		8.1	49.17		8.1	48.12	
CFGPD3025	8.58	21.40	22.41		31.08	31.51	8.54	37.78	37.00	8.6	47.08	46.26	8.6	52.11	46.83
b	8.61	23.06			31.97		8.58	36.21		8.6	45.87		8.6	47.59	
c	8.63	22.76			31.49		8.52	37.02		8.6	45.83		8.6	40.78	
CGMR5005	8.65	30.04	30.41	8.63	42.56	42.36	8.67	46.79	48.02	8.7	64.14	63.94	8.59	66.25	65.61
b	8.51	29.90		8.67	42.50		8.59	47.42		8.6	63.67		8.67	66.82	
c	8.59	31.28		8.69	42.02		8.66	49.84		8.7	64.00		8.66	63.76	
CS7300a	8.19	37.28	37.49	8.36	47.86	46.43	8.25	54.55	52.10	8.4	62.79	59.63	8.3	62.61	62.03
b	8.22	37.82		8.32	47.99		8.31	49.76		8.3	60.48		8.4	60.15	
c	8.25	37.38		8.16	43.44		8.39	51.92		8.4	55.61		8.4	63.34	
SC9100a	8.48	47.17		8.41	56.81		8.53	62.44		8.5	65.77		8.4	69.07	

			45.08			53.13			60.01			65.02			67.87
b	8.43	44.27		8.33	50.00		8.53	58.83		8.5	66.86		8.5	66.17	
c	8.47	43.79		8.40	52.59		8.40	58.75		8.5	62.44		8.5	68.38	
CSG5104a	8.19	13.97	13.69	8.26	19.78	21.29	8.18	26.03	28.10	8.2	37.24	40.49	8.3	42.92	39.96
b	8.31	13.12		8.18	19.12		8.35	30.61		8.5	42.59		8.2	38.18	
c	8.24	13.98		8.36	24.96		8.25	27.66		8.4	41.63		8.3	38.77	

Table A-9: Average Test Results for compressive strength for compressive and durability test series

Mix ID	**Sample Mass kg**					**Density Kg/m3**					**Fmax KN**					**σ MPa**				
	7	14	28	90	120	7	14	28	90	120	7	14	28	90	120	7	14	28	90	120
CCS	8.6	8.6	8.6	8.7	8.7	2546	2549	2856	2897	2566	1264	1283	1351	1588	1536	56.19	57.02	60.05	70.59	68.30
CSFB7111	8.3	8.3	8.3	8.3	8.4	2773	2771	2763	2464	2791	678	976	1124	1256	1370	30.12	43.37	49.95	55.83	60.89
CSFG4114	8.2	8.2	8.1	8.3	8.3	2739	2731	2714	2445	2756	470	696	838	1170	1171	20.89	30.95	37.26	52.00	52.02
CSFG4123	8.3	8.3	8.4	8.4	8.4	2771	2757	2793	2483	2796	332	703	925	1100	1263	20.20	31.24	41.12	48.88	56.13
CSFG4132	8.2	8.3	8.3	8.2	8.2	2734	2756	2754	2749	2732	393	651	827	1032	1175	17.46	28.94	36.75	45.87	52.22
CSFG4411	7.9	7.8	7.8	8.0	7.9	2619	2594	2610	2664	2636	463	663	725	1086	1063	20.56	29.46	32.20	48.25	47.23
CSFG4312	7.8	7.9	8.0	7.8	7.9	2594	2641	2678	2616	2626	377	626	862	1006	1029	16.75	27.82	38.29	44.71	45.72
CSFG4213	8.2	8.1	8.1	8.1	8.1	2731	2699	2700	2688	2713	430	673	830	1127	1231	19.10	29.90	36.90	50.09	54.69
CSFG4141	8.2	8.1	8.2	8.2	8.2	2718	2705	2722	2723	2739	365	587	791	1070	1101	16.22	26.07	35.14	47.57	48.95
CSFG4231	8.0	7.9	7.9	7.9	8.0	2656	2643	2667	2648	2679	408	592	743	960	964	18.11	26.29	33.04	42.68	42.86
CSFG4321	8.2	8.2	8.1	8.2	8.1	2730	2747	2700	2743	2688	549	794	895	1186	1127	24.40	35.30	39.75	52.69	50.06
CFGPD325	8.6	8.6	8.6	8.6	8.6	2550	2540	2548	2867	2543	504	709	833	1041	1054	22.41	31.51	37.00	46.26	46.83
CGMR5005	8.6	8.7	8.6	8.6	8.6	2543	2571	2561	2889	2560	684	956	1081	1439	1476	30.41	42.36	48.02	63.94	65.61
CS7300	8.2	8.3	8.3	8.4	8.3	2739	2760	2778	2796	2783	844	1045	1172	1342	1396	37.49	46.43	52.10	59.63	62.03
SC9100	8.5	8.4	8.5	8.5	8.5	2820	2793	2822	2829	2819	1014	1196	1350	1463	1527	45.08	53.13	60.01	65.02	67.87
CSG5104	8.2	8.3	8.3	8.4	8.3	2749	2755	2755	2787	2751	308	479	723	911	899	13.69	21.29	28.10	40.49	39.96

Table A-10: Specimens Unit-Weight for compressive and durability test series for different ages

Serial No	Mix ID	Slump	7 days	14 days	28 days	90 days	120 days
1	CCS	33	2546	2549	2856	2897	2566
2	CSFG7111	50	2773	2771	2763	2464	2791
3	CSFG4114	49	2739	2731	2714	2445	2756
4	CSFG4123	67	2771	2757	2793	2483	2796
5	CSFG4132	68	2734	2756	2754	2749	2732
6	CSFG4411	35	2619	2594	2610	2664	2636
7	CSFG4312	62	2594	2641	2678	2616	2626
8	CSFG4213	67	2731	2699	2700	2688	2713
9	CSFG4141	63	2718	2705	2722	2723	2739
10	CSFG4231	56	2656	2643	2667	2648	2679
11	CSFG4321	35	2730	2747	2700	2743	2688
12	CFGPD3025	65	2550	2540	2548	2867	2543
13	CGMR5005	49	2543	2571	2561	2889	2560
14	CS7300	20	2739	2760	2778	2796	2783
15	SC9100	20	2820	2793	2822	2829	2819
16	CSG5104	57	2749	2755	2755	2787	2751

Table A-11: Average test results for compressive strength of samples cured in an aggressive environemnts for 150days

Sodium Chloride Samples (Nacl)					Magnesium Sulphate Samples ($MgSO_4$)			
Mix ID	**Sample mass Kg**	**Density Kg/m^3**	**Fmax KN**	**σ MPa**	**Sample mass**	**Density Kg/m^3**	**Fmax KN**	**σ MPa**
CCS	8863	2954	1592	70.77	8761	2920	1365	60.67
CSFG7111	8501	2836	1254	55.73	8441	2814	1070	47.53
CSFG4114	8519	2840	1120	49.77	8517	2839	851	37.81
CSFG4123	8430	2810	1001	44.49	8439	2813	6723	29.88
CSFG4132	8302	2767	846	37.60	8351	2784	649	28.82
CSFG4411	8022	2674	839	37.30	8056	2686	592	26.32
CSFG4312	8001	2667	812	36.08	8089	2696	607	26.99
CSFG4213	8239	2746	975	43.33	8205	2735	679	30.19
CSFG4141	8347	2782	941	41.84	8333	2778	678	30.11
CSFG4231	8165	2722	902	40.09	8138	2713	617	27.43
CSFG4321	8093	2697	838	37.26	8147	2716	660	29.34
CFGPD3025	8680	2894	814	36.20	8702	2901	670	29.78
CGMR5005	8832	2944	1313	58.37	8773	2924	1185	52.66
CS7300	8132	2711	1073	47.70	8163	2721	996	44.25
SC9100	8428	2809	1185	52.65	8379	2793	1211	53.81
CSG5104	8334	2778	751	33.39	8334	2778	850	37.77

Table A-12: Workability and strength of the concrete specimen cured in a water for different ages

S/No	MIX ID	Slump (mm)	Compressive Strengths (MPa)						Comparison of 7 & 28 days strength
			7 days	14 days	28 days	90 days	120 days	W/B	% of 7 days to 28 days strength
1	Control Sample	33	56.19	57.02	60.05	70.59	68.30	0.5	94%
2	CSFG7111	50	30.12	43.37	49.95	55.83	60.89	0.5	60%
3	CSFG4114	49	20.89	30.95	37.26	52.00	52.02	0.5	56%
4	CSFG4123	67	20.20	31.24	41.12	48.88	56.13	0.5	49%
5	CSFG4132	68	17.46	28.94	36.75	45.87	52.22	0.5	48%
6	CSFG4411	35	20.56	29.46	32.20	48.25	47.23	0.5	64%
7	CSFG4312	62	16.75	27.82	38.29	44.71	45.72	0.5	44%
8	CSFG4213	67	19.10	29.90	36.90	50.09	54.69	0.5	52%
9	CSFG4141	63	16.22	26.07	35.14	47.57	48.95	0.5	46%
10	CSFG4231	56	18.11	26.29	33.04	42.68	42.86	0.5	55%
11	CSFG4321	35	24.40	35.30	39.75	52.69	50.06	0.5	61%
12	CFGPD3025	65	22.41	31.51	37.00	46.26	46.83	0.5	61%
13	CGRM5005	49	30.41	42.36	48.02	63.94	65.61	0.5	63%
14	CS7300	20	37.49	46.43	52.10	59.63	62.03	0.5	72%
15	CS9100	20	45.08	53.13	60.01	65.02	67.87	0.5	75%
16	CSG5104	57	13.69	21.29	28.10	40.49	39.96	0.5	49%

Table A-13: Compressive strengths of the specimens with corresponding load at crushing point

Materials			Load (KN) Vs. Compressive Strength (MPa)									
	SCMs %	Load (KN)	7 days	Load (KN)	14 days	Load (KN)	28 days	Load (KN)	90 days	Load (KN)	120 days
1	Control Sample	1264	56.19	1283	57.02	28	60.05	1588	70.59	1536	68.30
2	CSFG7111	678	30.12	976	43.37	1351	49.95	1256	55.83	1370	60.89
3	CSFG4114	470	20.89	696	30.95	1124	37.26	1170	52.00	1171	52.02
4	CSFG4123	332	20.20	703	31.24	838	41.12	1100	48.88	1263	56.13
5	CSFG4132	393	17.46	651	28.94	925	36.75	1032	45.87	1175	52.22
6	CSFG4411	463	20.56	663	29.46	827	32.20	1086	48.25	1063	47.23
7	CSFG4312	377	16.75	626	27.82	725	38.29	1006	44.71	1029	45.72
8	CSFG4213	430	19.10	673	29.90	862	36.90	1127	50.09	1231	54.69
9	CSFG4141	365	16.22	587	26.07	830	35.14	1070	47.57	1101	48.95
10	CSFG4231	408	18.11	592	26.29	791	33.04	960	42.68	964	42.86
11	CSFG4321	549	24.40	794	35.30	743	39.75	1186	52.69	1127	50.06
12	CFGPD3025	504	22.41	709	31.51	895	37.00	1041	46.26	1054	46.83
13	CGRM5005	684	30.41	956	42.36	833	48.02	1439	63.94	1476	65.61
14	CS7300	844	37.49	1045	46.43	1081	52.10	1342	59.63	1396	62.03
15	CS9100	1014	45.08	1196	53.13	1172	60.01	1463	65.02	1527	67.87
16	CSG5104	308	13.69	479	21.29	1350	28.10	911	40.49	899	39.96

Table A-14: Compressive strengths of reinforced concrete specimens in the media (NaCl, $MgSO_4$ & H_2O)

S/No	MIX ID	Compressive Strengths cured in aggressive medium for 150days (MPa)		Compressive strengths cured in water for 120days (MPa)
		NaCl	$MgSO_4$	H_2O
1	CCS	70.77	60.67	68.30
2	CSFG7111	55.73	47.53	60.89
3	CSFG4114	49.77	37.81	52.02
4	CSFG4123	44.49	29.88	56.13
5	CSFG4132	37.60	28.82	52.22
6	CSFG4411	37.30	26.32	47.23
7	CSFG4312	36.08	26.99	45.72
8	CSFG4213	43.33	30.19	54.69
9	CSFG4141	41.84	30.11	48.95
10	CSFG4231	40.09	27.43	42.86
11	CSFG4321	37.26	29.34	50.06
12	CFGPD3025	36.20	29.78	46.83
13	CGRM5005	58.37	52.66	65.61
14	CS7300	47.70	44.25	62.03
15	CS9100	52.65	53.81	67.87
16	CSG5104	33.39	37.77	39.96

Table A-15: % Difference of 7 days strength over 14, 28, 90, and 120 curing days

MIX	7	14	28	90	120
CCS	100	98.5	93.6	79.6	82.3
CSFG7111	100	69.4	60.3	54	49.5
CSFG4114	100	67.5	56.1	40.2	40.2
CSFG4123	100	64.7	49.1	41.3	36
CSFG4132	100	60.3	47.5	38.1	33.4
CSFG4411	100	69.8	63.9	42.6	43.5
CSFG4312	100	60.2	43.7	37.5	36.6
CSFG4213	100	63.9	51.8	38.1	35
CSFG4141	100	62.2	46.2	34.1	33.1
CSFG4231	100	68.9	54.8	42.4	42.3
CSFG4321	100	69.1	61.4	46.3	48.7
CFGPD3025	100	71.1	60.6	48.4	47.9
CGRM5005	100	71.8	63.3	47.6	46.3
CS7300	100	80.7	72	62.9	60.4
CS9100	100	84.8	75	69.3	66.4
CSG5104	100	64.3	48.7	33.8	34.3

Table A-16: Change in compressive strength relative to control (workability & Durability Series)

S.No	Mix ID	Compressive Strengths				
		7	14	28	90	120
1	Control	56.19	57.02	60.05	70.59	68.30
2	CSFG7111	30.12	43.37	49.95	55.83	60.89
3	CSFG4114	20.89	30.95	37.26	52.00	52.02
4	CSFG4123	20.20	31.24	41.12	48.88	56.13
5	CSFG4132	17.46	28.94	36.75	45.87	52.22
6	CSFG4411	20.56	29.46	32.20	48.25	47.23
7	CSFG4312	16.75	27.82	38.29	44.71	45.72
8	CSFG4213	19.10	29.90	36.90	50.09	54.69
9	CSFG4141	16.22	26.07	35.14	47.57	48.95
10	CSFG4231	18.11	26.29	33.04	42.68	42.86
11	CSFG4321	24.40	35.30	39.75	52.69	50.06
12	CFGPD3025	22.41	31.51	37.00	46.26	46.83
13	CGRM5005	30.41	42.36	48.02	63.94	65.61
14	CS7300	37.49	46.43	52.10	59.63	62.03
15	CS9100	45.08	53.13	60.01	65.02	67.87
16	CSG5104	13.69	21.29	28.10	40.49	39.96

Table A-17: % Change in compressive strength relative to control (Workability & Durability Series)

S.No	Mix ID	Compressive Strengths				
		7	14	28	90	120
1	Control	Datum	Datum	Datum	Datum	Datum
2	CSFG7111	-46	-24	-17	-21	-11
3	CSFG4114	-63	-46	-38	-26	-24
4	CSFG4123	-64	-45	-32	-31	-18
5	CSFG4132	-69	-49	-39	-35	-24
6	CSFG4411	-63	-48	-46	-32	-31
7	CSFG4312	-70	-51	-36	-37	-33
8	CSFG4213	-66	-48	-39	-29	-20
9	CSFG4141	-71	-54	-41	-33	-28
10	CSFG4231	-68	-54	-45	-40	-37
11	CSFG4321	-57	-38	-34	-25	-27
12	CFGPD3025	-60	-45	-38	-34	-31
13	CGRM5005	-46	-26	-20	-9	-4
14	CS7300	-33	-19	-13	-16	-9
15	CS9100	-20	-7	0	-8	-1
16	CSG5104	-76	-63	-53	-43	-41

Table A-18 : Materials Properties

Given	Cement	Type Dc	CEM 1 52.5N 3.14	Design Mix Ratio	
	Sand	Ds FM	2.94 3.68	Cement	420kg/m3
	Stone	Da Size CBD	2.921 22.4mm 1648kg/m3	Coarse Aggregates	1091kg/m3
Required	Degree of Control		“Average”	Sand	824.66kg/m3
	Characteristics strength at 28 days		25Mpa	Water	210kg/m3
	Consistence		75mm slump for moderate vibration		
	Maximum w:c for durability				0.5

Table A – 19: Rate of Corrosion in tested coupons results

	Sodium Chloride measurements					Magnesium Sulphate measurements				
Mix ID	Time (Days	Weight change (g)	Area	Density Kg/m^3	Corrosion Rate	Time (Days)	Weight Change (g)	Area	Density Kg/m^3	Corrosion Rate
CCS	167	2	51.3	7.85	0.108423	167	2	51.3	7.85	0.108423473
	172	2	51.3	7.85	0.105272	172	2	51.3	7.85	0.105271628
	177	2	51.3	7.85	0.102298	177	0	51.3	7.85	0
CSFG7111	167	1	51.3	7.85	0.054212	167	0	51.3	7.85	0
	172	1	51.3	7.85	0.052636	172	1	51.3	7.85	0.052635814
	177	1	51.3	7.85	0.051149	177	1	51.3	7.85	0.051148926
CSFG4114	167	0	51.3	7.85	0	167	1	51.3	7.85	0.054211736
	172	1	51.3	7.85	0.052636	172	2	51.3	7.85	0.105271628
	177	1	51.3	7.85	0.051149	177	2	51.3	7.85	0.102297853
CSFG4123	167	1	51.3	7.85	0.054212	167	1	51.3	7.85	0.054211736
	172	2	51.3	7.85	0.105272	172	0	51.3	7.85	0
	177	2	51.3	7.85	0.102298	177	2	51.3	7.85	0.102297853
CSFG4132	167	2	51.3	7.85	0.108423	167	1	51.3	7.85	0.054211736
	172	0	51.3	7.85	0	172	0	51.3	7.85	0
	177	0	51.3	7.85	0	177	2	51.3	7.85	0.102297853
CSFG4411	167	2	51.3	7.85	0.108423	167	0	51.3	7.85	0
	172	1	51.3	7.85	0.052636	172	1	51.3	7.85	0.052635814
	177	2	51.3	7.85	0.102298	177	2	51.3	7.85	0.102297853
CSFG4312	167	2	51.3	7.85	0.108423	167	1	51.3	7.85	0.054211736
	172	2	51.3	7.85	0.105272	172	0	51.3	7.85	0
	177	2	51.3	7.85	0.102298	177	0	51.3	7.85	0
CSFG4213	167	1	51.3	7.85	0.054212	167	1	51.3	7.85	0.054211736
	172	0	51.3	7.85	0	172	1	51.3	7.85	0.052635814
	177	1	51.3	7.85	0.051149	177	0	51.3	7.85	0
CSFG4141	167	0	51.3	7.85	0	167	3	51.3	7.85	0.162635209
	172	0	51.3	7.85	0	172	3	51.3	7.85	0.157907442
	177	2	51.3	7.85	0.102298	177	2	51.3	7.85	0.102297853
	167	1	51.3	7.85	0.054212	167	0	51.3	7.85	0

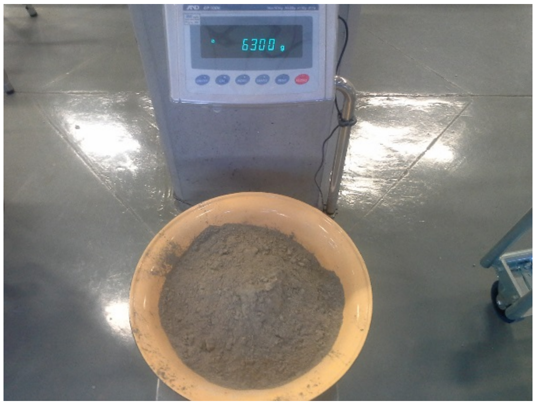
CSFG4231	172	1	51.3	7.85	0.052636	172	0	51.3	7.85	0
	177	1	51.3	7.85	0.051149	177	1	51.3	7.85	0.051148926
CSFG4321	167	1	51.3	7.85	0.054212	167	1	51.3	7.85	0.054211736
	172	2	51.3	7.85	0.105272	172	1	51.3	7.85	0.052635814
	177	1	51.3	7.85	0.051149	177	0	51.3	7.85	0
CFGPD3025	167	0	51.3	7.85	0	167	1	51.3	7.85	0.054211736
	172	0	51.3	7.85	0	172	1	51.3	7.85	0.052635814
	177	1	51.3	7.85	0.051149	177	1	51.3	7.85	0.051148926
CGMR5005	167	0	51.3	7.85	0	167	0	51.3	7.85	0
	172	1	51.3	7.85	0.052636	172	1	51.3	7.85	0.052635814
	177	1	51.3	7.85	0.051149	177	0	51.3	7.85	0
CS7300	167	0	51.3	7.85	0	167	0	51.3	7.85	0
	172	1	51.3	7.85	0.052636	172	1	51.3	7.85	0.052635814
	177	0	51.3	7.85	0	177	2	51.3	7.85	0.102297853
SC9100	167	0	51.3	7.85	0	167	1	51.3	7.85	0.054211736
	172	1	51.3	7.85	0.052636	172	0	51.3	7.85	0
	177	0	51.3	7.85	0	177	0	51.3	7.85	0
CSG5104	167	0	51.3	7.85	0	167	0	51.3	7.85	0
	172	0	51.3	7.85	0	172	0	51.3	7.85	0
	177	2	51.3	7.85	0.102298	177	0	51.3	7.85	0

APPENDIX B: SAMPLES SEQUENCE

B-1 COMPRESSIVE STRENGTH TEST

22 mm aggregates

Unwashed crusher sand



OPC Cement Class 52.5N

Fly Ash

Coarse aggregates in oven at 110ºC

Fine aggregates in oven at 110ºC

50 Litre Mixing Drum

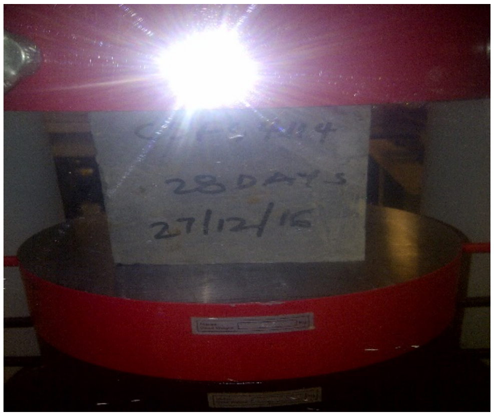
Cement constituents in a 50 L Drum

Casting in Progress

Concrete covered with polythene material

Fresh concrete ready to be transferred Into curing tan

Concrete samples in a curing tank



Sample under crushing at 28 days

Sample under crushing at 90 days

B-2 DURABILITY TEST

Disc sample being measured

Discs samples in PVC sheath

A complete experimental setup

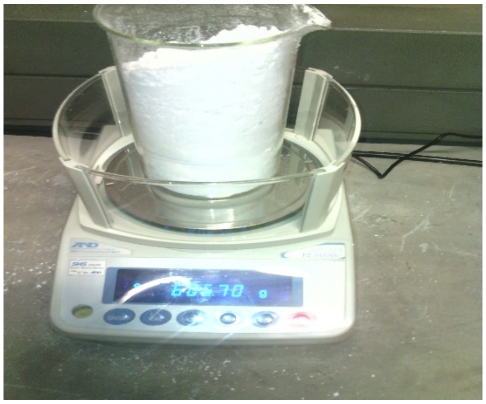
Disc specimen sealed with tape

Discs in calcium hydroxide solution

Chlorine Conductivity exp. set up

B-3 CORROSION TEST

Sodium Chloride on a weighing scale

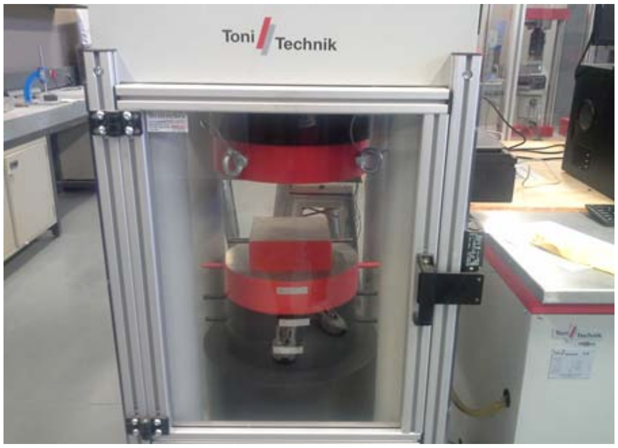


Magnesium Sulphate on a weighing scale

Reinforced samples in the media

APPENDIX C: EQUIPMENT SEQUENCE

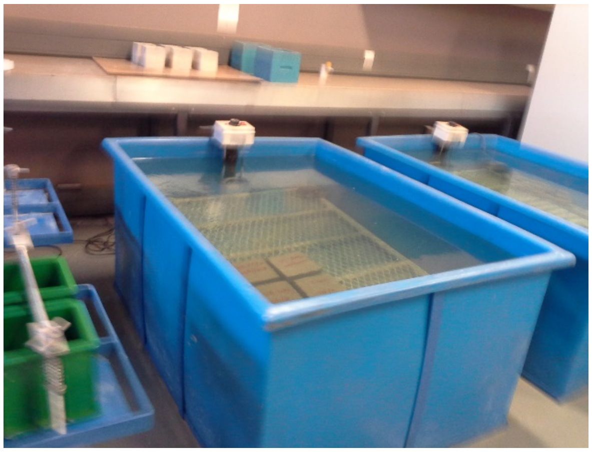
Mixing Drum



Compressive strength testing machine

Oven

Oxygen permeability set up



Curing Tank

Chlorine Conductivity Experimental Set up