OPTIMIZING THE USAGE OF FLY ASH IN CONCRETE MIXES

By

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APPROVAL FOR FINAL SUBMISSION

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DECLARATION

I, Sabelo N.F Zulu hereby declare that the work contained in this dissertation is my own original work, and that;

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This research was conducted at the Durban University of Technology under the supervision of Professor Dhiren Allopi.

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ABSTRACT

Improving on our construction practices to promote sustainable development in engineering and to promote eco-friendly living is vital in the fight against global warming and associated problems. This study looked at one of the ways in which engineering can contribute to this fight through promoting the recycling of waste by-products such as fly ash (FA), on a larger scale in the cement and concrete industry, by utilizing the FA to the optimum.

In this study concrete mixes of 25 MPa, 35 MPa and 50 MPa with FA partially substituting the cement at 30%, 40%, 50% and 60% were produced and numerous tests were performed to determine the optimum amount of FA that can be used and still obtain better or comparable concrete to ordinary concrete. Testing for concrete properties was conducted under laboratory conditions over a period of one year. In addition, a cost comparison between ordinary concrete and FA concrete was undertaken.

The results obtained show that the increase in FA content influenced the rheological properties of fresh concrete favorable. The recorded slump increased with the increase of FA content. Increasing the FA content prolonged the setting of concrete, with the ordinary concrete taking 1 hour 45 min to set, compared to more than 2 hours for FA mixes. The FA increase had negligible effects on the air content of the concrete mixes. The drying shrinkage of concrete increased with the increase of FA content, with the strain ranging from 0,045% to 0,56%.

The compressive strength results show that the control mixes with 30% FA content attained the highest compressive strength over a year. In some cases, the 40% FA strength was compatible to the 30% FA strength. The durability index results showed the control mix of 30% FA attaining better results for Oxygen Permeability Index and Sorptivity Index, with the 40% FA mix following closely. The higher FA content mixes (50% and 60%) attained better Chloride Conductivity results than the lower FA content mixes.

Increasing the FA content does affect the performance of the concrete at early stages, however concrete with acceptable strength and good durability qualities can be produced even with 50% FA volume. Increasing the FA content can also significantly reduce the cost of producing and working with concrete. The practice of utilizing higher FA content in concrete can be beneficial for the South African cement and concrete industry without compromising the quality of the cement products concrete structures.

Keywords: Concrete, cement, durability, environment, fly ash, HVFA, permeability, pozzolan, strength and workability.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ACI	- American Concrete Institute
ASTM	- American Society for Testing and Materials
BS	- British Standards
C&CI	- Cement and Concrete Institute
$Ca(OH)_2$	- Calcium Hydroxide
CaO	- Calcium Oxide
CC	- Chloride Conductivity
CEM	- Cement
CO_2	- Carbon Dioxide
CSF	- Condensed Silica Fumes
CSH	- Calcium Silicate Hydrate
DUT	- Durban University of Technology
FA	- Fly Ash
FL	- Flow Table Test
FM	- Fineness Modulus
GBFS	- Granulated Blast-furnace Slag
HVFA	- High Volume Fly Ash
kg	- Kilogram
kPa	- Kilopascals
LEED	- Leadership in Energy and Environmental Design
LOI	- Loss on Ignition
MPa	- Megapascals
NaCl	- Sodium Chloride
NPC	- Natal Portland Cement
OPI	- Oxygen Permeability Index
PC	- Portland Cement
PCA	- Portland Cement Association
PFA	- Pulverized Fly Ash
PPC	- Premium Portland Cement
PSD	- Particle Size Distribution
RCC	- Roller Compacted Concrete
RHPC	- Rapid Hardening Portland Cement
SABS	- South African Bureau of Standards
SANS	- South African National Standards

SCM - Supplementary Cementitious Material
SiO_2 - Silicon Dioxide
SL - Slump Test
SRPC - Sulphate Resisting Portland Cement
SSD - Saturated Surface Dry
UNFCCC - United Nations Framework Convention on Climate Change
W/CM - Water-to-Cementitious Material

PREFACE

PUBLICATIONS AND CONFERENCES

1. **Institutional Research Day, Durban University of Technology, 2013:**
   Zulu, S. and Allopi, D. 2013. Optimizing the use of fly ash in roads construction. DUT Institutional Research Day, Durban, South Africa, November 2013.

2. **Publication in the International Journal of Engineering and Innovative Technology (IJEIT), 2014- ISSN: 2277-3754 :**
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3. **Built Environment Conference ASOCSA2014:**
   Zulu, S. and Allopi, D. 2014. Optimizing the usage of fly ash in concrete. 8th Built Environment Conference ASOCSA2014 - SGB11A, Durban, South Africa, July 2014.

4. **Southern African Transport Conference 2015:**
   Zulu, S. and Allopi, D. 2015. Optimizing the usage of fly ash in concrete in the construction of roadworks. The 34th Annual Southern African Transport Conference and Exhibition, Pretoria, South Africa, July 2015.

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6. **CBI Africa Conference 2016 (Guest Speaker):**
   Zulu, S. and Allopi, D., 2016. Evaluating the effects of utilizing high fly ash content in concrete. The Cement Business and Industry Africa 2016, Johannesburg, South Africa, June 2016.

7. **Publication in the Invention Journal of Research Technology in Engineering & Management (IJRTEM), 2016- ISSN: 2455-3689:**

   Zulu, S. and Allopi, D., 2016. Evaluating the performance of high-volume fly ash (HVFA) concrete, for South African fly ash. Invention Journal of Research Technology in Engineering & Management (IJRTEM)

CHAPTER 1

1 INTRODUCTION

1.1 Background to the study

The earth's ecosystem today is faced with the growing problem of global warming which is largely associated with the emission of Carbon Dioxide (CO_2) into the atmosphere. The global warming is bringing about climate change which is largely a result of human activities, such as the production of cement, that produce greenhouse gases. Every intervention that helps to mitigate such problems is greatly welcomed.

Many companies around the globe are now facing the pressures of complying with various international environmental laws and regulations such as South African National Standards (SANS) 14001:2015 (2015), and they are re-examining their business operations in a fundamental way. They are exploring the concept of "sustainable development", seeking to integrate their pursuit of profitable growth with the assurance of environmental protection and quality of life for present and future generations. Based on this new perspective, some companies are beginning to make significant changes in their policies, commitments and business strategies (Marlowe and Mansfield, 2002: i).

The construction industry contributes profusely to the emission of CO_2 through heavy construction equipment and plant, and through the production of construction materials such as cement and concrete. Inventions and/or improvements on sustainable construction methods will go a long way in promoting sustainable development and provide relief for the environment.

Power plants fueled by coal produce half the electricity we consume every day, but in addition, they produce a material that is fast becoming a vital ingredient for improving the performance of a wide range of concrete products. That material is "Fly Ash" (FA).

It has been reported that about one billion tonnes of FA is produced annually worldwide in coal-fired steam power plants, and only a small part of this ash is used (20%–30%); the rest is landfilled and surface-impounded, with potential risks of air pollution and contamination of water due to leaching (Fernandez-Jimenez and Palomo, 2005: 1984).

FA is utilized in concrete as a cement extender and has contributed a lot in reducing a carbon footprint generated due to the cement production. To reduce the CO_2 emissions related to cement production, the use of Portland Cement (PC) in the concrete and cement industry should be reduced without compromising the quality and performance of concrete structures.

1.2 Statement of the problem

The main environmental issues associated with cement production are emissions of CO_2 to the atmosphere and immense energy use. Among the greenhouse gases, CO_2 contributes about 65 percent of the global warming (Rashad, 2015: 279), and the cement production accounts for about eight percent of global human-generated CO_2 emissions (Gilies, 2001: 1). The production of cement emits approximately one tonne of CO_2 per tonne of cement produced into the atmosphere. The energy consumed by the cement industry is estimated to be about two percent of global primary energy consumption (Marlowe and Mansfield, 2002: 3).

Each tonne of FA used as a supplementary cementitious material (SCM) in cementitious products saves approximately one tonne of CO_2. It is estimated that in the last decade, the cement and construction industries in South Africa have saved the country in excess of six million tonnes of harmful greenhouse gas emissions by incoporating FA in cement and concrete products (Ash Resources, 2009: 4). The emission of CO_2 is not the only problem currently facing the construction industry. The increase in the volume of construction in the last decade has resulted in over exploitation of our natural resources.

The natural resources used in concrete are finite, and so the sustainability of construction needs to be taken into consideration (Camoes, Aguiar and Jalali, 2003). Concrete is second only to water as the most consumed substance on earth, with nearly three tonnes of the material used annually for each person on the planet. Cement is the critical ingredient in concrete, locking together the sand and gravel constituents in an inert matrix (Marlowe and Mansfield, 2002: 2). A usage of a tonne of FA to replace a tonne of other manufactured materials such as cement, saves enough electricity to power an average American home for 24 days, and reduces CO_2 emissions equal to two months' use of an automobile (Headwaters Resources, 2014: 11).

In South Africa, Eskom's fired power stations consume approximately 109 million tonnes of coal per annum that produce about 25 million tonnes of ash. Only about 1.2 million tonnes per year of that ash is sold to the cement industry (Eskom, 2016). Utilizing FA optimally at volumes higher than 30% can play a big role in disposing the by-product in a responsible and environmentally friendly practice while promoting sustainable development.

1.3 Research significance in the South African industry

As a developing country, South Africa has a responsibility of ensuring responsible sustainable development that is in line with the United Nations Framework Convention on Climate Change (UNFCCC). The cement and concrete industry contributes immensely in the infrastructure development to the detriment of some of natural resources. Utilizing FA in cement and concrete products plays an important role of promoting sustainable developments. Optimizing the usage of FA can benefit the industry considerable and research should be encouraged to ensure the promotion of FA usage does not come with a negative impact in the engineering industry.

There are studies done globally regarding the utilization of higher content of FA in concrete. A number of these studies come to favorable conclusions about the practice of utilizing higher FA content, however sum of the studies have some reservations on certain aspects of this practice, such as the performance of concrete when it comes to early strength gain and some durability aspects. This has led to some resistance in convincing many engineers to start specifying higher content of FA than the conventional amount of up to 30%.

In South Africa, there have not been many studies that look into the utilization of high FA content, even though the practice is slowly becoming prevalent. Research has shown that utilizing concrete with higher FA content can be beneficial in terms of mechanical and durability properties of concrete. They also show that it should have economic and environmental benefits. Most of FA in South Africa is sourced from ESKOM plants and they are planning to increase the amount of FA that can be used commercially instead of disposing the product.

This study is aiming in determining an optimum amount of FA that can be used in South African concrete industry by determining a volume that FA can substitute cement in concrete and still result in concrete that is better or comparable to the conventional

30% FA concrete. Studies such as this are stepping-stones into understanding unconventional engineering practices that can be applied to promote sustainable development.

1.4 Fly ash in concrete

FA comprises the non-combustible mineral portion of coal. When coal is consumed in a power plant, it is first ground to the fineness of powder which is blown into the power plant's boiler where the carbon is consumed, leaving molten particles rich in silica, alumina and calcium. These particles solidify as microscopic, glassy spheres that are collected from the plant exhaust before they fly away (Headwaters Resources, 2014: 02). The recognition that FA frequently exhibits pozzolanic properties has led to its use as a constituent of concrete by partially replacing the cement. When mixed with lime, also known as Calcium Hydroxide ($Ca(OH)_2$), liberated from the cement during hydration, pozzolans combine to form cementitious compounds (Headwaters Resources, 2014: 04).

FA can be categorized as a cementitious material when CaO is greater than 20% or as a cementitious and pozzolanic material when CaO varies between 10% and 20%. Research studies performed globally indicate that the spherical shape of FA particles and their extreme fineness have a beneficial effect on the workability of concrete (Ozdemir, Ersoy and Celik, 2001). The replacement level of Class F FA in concrete is generally between 15% and 40% by mass of cementitious material (Feng and Clark, 2011: 1). There are many case studies of FA being used as a cement substitute in concrete beyond 50%, however this phenomenon is hardly reconnoitered in South Africa.

There is a growing trend globally of using high volume of FA in concrete mixes, driven by three main factors. The first factor is the economic benefits; FA is a by-product and is generally cheaper than cement. A study conducted by Pitroda, and Umrigar (2012) found that reduction in cement content resulted in a decrease in cost. The second factor is the environmental benefits; FA is usually deposited into landfills for disposal, which can take its toll on the environment. Furthermore, the demand for the manufacturing of PC is reduced due to the increased use of FA. Van den Heede et al. (2010) conducted a life cycle assessment calculation which showed that when using high-volume fly ash (HVFA) concrete the amount of CO_2 emitted is 25.8% less compared to traditional concrete which is normally used under the same circumstances. The third factor is the technical benefits; the incorporation of FA in concrete tends to affect the characteristics and properties of concrete positively.

The method of partially replacing cement with a high volume of FA has generated considerable interest in recent years (Rashad, 2015: 280). Many Engineers, however, are reluctant in specifying concrete with high FA volume with one main concern being that the early strength development of FA concrete under standard curing conditions is usually slower than that of PC concrete. FA cement, along with other supplementary cementitious materials such as slag, is therefore not commonly used in applications where high early-age strength is required (Barnett et al., 2007: 388).

ASTM C 618-15 (2015) states that the optimum amount of fly ash or natural pozzolan for any specific project is determined by the required properties of the concrete and other constituents of the concrete and is to be established by testing.

1.5 Objectives of the study

The objectives of this study were as follows:

- To develop three concrete mix designs of 25 MPa, 35 MPa and 50 MPa with 30% FA content, to be used as control mixes for preliminary compressive strength testing at 28-days,
- To undertake testing of fresh concrete properties, such as consistency, shrinkage and setting time, on four 35 MPa FA concrete mixes, with FA content of 30%, 40%, 50% and 60%, to evaluate the influence of increasing the volume of FA in the mix,
- To evaluate the durability properties of the four 35 MPa concrete mixes with different FA contents at 7-days and 28-days periods,
- To perform compressive strength tests on laboratory specimens made from 25 MPa, 35 MPa and 50 MPa concrete with four levels of FA content, for evaluating the performance of the different FA concrete mixes at different high FA volumes over a period of one year,
- To carry out a cost comparison of different FA concrete mixes and ordinary cement concrete mixes and
- To compare the performance of FA concrete mixes, from the results obtained, to determine an optimum level of FA content a concrete mix would perform better or comparable to a standard FA concrete.

1.6 Scope of the study

This study looks at the properties of concrete mixes with unclassified FA as a cement extender at various high volumes (40%, 50% and 60%) compared to the customary 30% FA concrete mix that is usually specified by engineers, as directed under SANS 50197-1 (2000). Properties such as the compressive strength, durability, air content, setting time and shrinkage are evaluated through performing laboratory testing. The tests are performed under laboratory conditions in-line with the normal construction industry practice in South Africa. In addition, a cost comparison of different FA concrete mixes, for different concrete grades, is conducted. The results from the performed tests are discussed in details to reach certain conclusions. Recommendations, based on the obtained results, are made regarding the increasing of FA usage.

1.7 Methodology

This study was undertaken by conducting fresh and hardened concrete tests, which are usually performed in the South African construction industry, under laboratory conditions. Concrete mixes of grades 25 MPa, 35 MPa and 50 MPa, with each grade having cement substituted at four levels of 30%, 40%, 50% and 60% were designed and specimens were made, for performing the laboratory tests and evaluating the plastic properties, the mechanical properties and the durability properties of the FA concretes.

1.7.1 Making of specimens

Concrete samples for compressive strength test were made by hand mixing at the Durban University of Technology laboratory and the concrete samples used for fresh concrete properties and durability testing were made at Contest Laboratory, in Pinetown, in an electric pan mixer.

1.7.2 Testing

Testing of fresh concrete for tests such as Slump test, Time of Set, Linear Shrinkage and air content was performed on the 35 MPa concrete mixes with four FA substitution levels. In addition, durability index test such as Oxygen Permeability Index (OPI), Chloride Conductivity (CC) and Sorptivity Index (SI) were performed on the 35 MPa concrete specimens. The compressive strength tests were performed using a hydraulic press machine. The tests performed were standard concrete industry tests that are usually performed regularly when working with large quantities of concrete.

1.7.3 Analysis of test results

The results obtained from the performed tests are analyzed, to evaluate the performance of the FA concrete mixes with respect to different FA content. An optimum FA mix, in terms of FA content, should obtain results that are acceptable in terms of concrete specifications, and can be better or comparable to the 30% FA mix, in terms of compressive strength and durability test results, as these tests are commonly used to indicate the performance of structural concrete. Furthermore, a cost comparison of concrete mixes with different FA volumes is done to determine how the increase of FA can affect the cost of producing concrete.

1.8 Research Limitations

There are many types of tests performed to evaluate the performance of concrete under different conditions. Only those that are commonly performed in the construction industry, such as compressive strength and durability tests, are performed in the study. For durability index, the three durability index tests developed for the South African industry are performed. In addition, some tests are performed for the evaluation of plastic properties such as workability, air content and setting time.

Although some physical and chemical properties of FA can have a certain effect on concrete with regard to its performance, like where problems can arise when high carbon FA is used in air-entrained concrete with certain air-entraining admixes (Ash Resources, 2009: 8), this study is not concerned with the FA properties. In some cases, FA can be activated with alkaline activators to produce pastes that can set and harden in reasonably short periods. Although this could be a welcomed characteristic of FA pastes, it is not evaluated in this study, as the alkali activation process in not commonly practiced in the construction industry.

In recent years, the cement industry has been incorporating FA as an SCM in ternary mixes such as “slagment”. Such mixes have been extensively utilized in the industry with good success; however, this study is only evaluating the performance of FA as the only cement extender in concrete, as there is a growing interest in the cement and concrete industry to increase the usage of FA in concrete products.

1.9 Overview of chapters

This dissertation comprises five chapters and a brief overview of the chapters is presented below:

- **Chapter 1 – Introduction**

This introduction chapter provides a brief description of the study background and what gives rise to the undertaking of the research. Brief information on FA is given and the reasons that necessitated the research. The problem statement, study objectives, the scope of works, methodology, delimitations and overview of the study chapters are discussed.

- **Chapter 2 – Literature review**

This chapter mainly discusses the previous studies and literature done on the extent of the usage of FA in concrete. From this chapter we get an extent to which the FA has been used as a cement substitute in concrete, with palpable benefits worldwide.

- **Chapter 3 – Laboratory work**

This chapter provides details on the methodology and the materials utilized in this study. In addition, the type of tests and testing procedures used at the laboratories are discussed.

- **Chapter 4 – Results and discussion**

The results obtained from the laboratory testing are presented, analyzed and discussed in this chapter. Testing for compressive strength, durability, workability, setting time and shrinkage is discussed. The cost analysis of the different FA mixes is presented and discussed.

- **Chapter 5 – Conclusions and recommendations**

This chapter discusses the conclusions reached and recommendations arising from the analysis of the results obtained from the laboratory testing of concrete specimens.

1.10 Conclusion

After the testing of the concrete specimens, the results are presented and discussed to reach the conclusions and recommendations. From other studies conducted worldwide regarding FA in concrete, it is expected that the optimum amount of FA can be increased above the standard 30% regulation.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

Most of the cement producers produce blended cements, by inter-grinding or blending cement clinker with other materials such as granulated blast-furnace slag (GBF) and pulverised fly ash (PFA), to provide for benefits in performance associated with the blended materials. In some cases FA is used as the only cement extender in concrete mixes due to its perceived good workability and durability properties. Due to rapid economic development and infrastructure growth globally, the production and consumption of energy has significantly increased, and FA availability has also increased. Therefore, FA should not only be disposed of safely to prevent environmental pollution, but should be treated as a valuable construction resource (Rashad, 2015: 280).

The utilization of FA as a cement extender does not only provide benefits in the construction industry in terms of structural performance, but also plays a significant economic role. This practice promotes sustainable development in terms of reducing the carbon footprint which is associated with the production of cement, and reducing the amount of the by-product that is disposed at the landfills.

2.2 Background

FA has long being used as a partial substitute of cement in concrete for a long time as it is considered a pozzolan, which is a term coined from the small Italian town of *Pozzuoli,* where some of the first hydraulic cements were created over 2000 years ago (Lafarge North America, 2007: 2). FA is a finely divided amorphous alumino-silicate with varying amounts of calcium. When mixed with cement and water, FA reacts with the calcium hydroxide released by the hydration of cement to produce various calcium-silicate hydrates (C-S-H) and calcium-aluminate hydrates (Thomas, 2007: 2). Due to its pozzolanic properties, the usage of FA in concrete has been favored worldwide and the cement industry has started experimenting with increasing the substitution volumes for more benefits.

The ever-increasing infrastructure development comes with the increase in the demand and consumption of cement, it is therefore becoming very important that the concrete and cement industry starts developing sustainable alternatives. Utilizing more FA in cement products should be practiced commonly, to meet the cementitious materials demands instead of only increasing cement production. In Western Canada, EcoSmart (an industry-government partnership) is aggressively promoting the use of high-volume FA (HVFA) in concrete construction. Also, reducing CO_2 emissions through the increased use of FA is part of the Canadian federal government's Action Plan 2000 on climate change (Burden, 2006: 3). EcoSmart has coined the term "EcoSmart concrete" and defines it as concrete produced by replacing roughly half of the cement used in conventional concrete with a supplementary cementing material such as FA (Burden, 2006: 7). In the USA, FA use in concrete qualifies for credit under the Leadership in Energy and Environmental Design (LEED) rating system for sustainable construction (Headwaters Resources, 2014: 11).

2.3 Overview of fly ash usage in concrete

FA is widely used in concrete for economic and durability considerations as a partial replacement of cement. FA is extracted by electrostatic precipitators from the flue gases of furnaces and about 10 percent of fine fraction retained from the 45-µm sieve is used as a cement extender while the coarse fraction is discarded (Addis, 1994a: 12). FA has to meet American Society for Testing and Materials (ASTM) standard ASTM C618 (2015), which is the standard specification for coal FA and raw or calcined natural pozzolan for use in concrete. This by itself is adequate for specifying FA in concrete (Obla, 2008: 62).

In South African specifications, SANS 50197-1 (2000), for FA content as an extender, the usage of FA is limited to around 30 percent of binder material (Kearsley and Wainwright, 2003: 20). However, the increase of the FA content could result in better performing cement and greater environment protection as a result of less cement production in the long term. When FA was originally used in concrete in the 1970s, there was some basis for restricting its use such as slower early strength development. However, after extensive research and several decades of successful utilization of FA, it seems the 30 percent restriction on the quantity of FA that should be permitted to be used in concrete may not be warranted (Obla, 2008: 60). From theoretical considerations and practical experience, Malhotra and Mehta, 2002 (cited in Mehta, 2004: 6) determined that, sustainable and high-performance concrete mixes that show high workability, high ultimate strength, and high durability can be produced with 50 percent or more cement replacement by FA.

Table 2.1: Types of cement compositions available in South Africa (Cement and Concrete Institute, 2009).

Main types	Notation of products (types of common cement)		Composition, percentage by mass[(a)]										
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		Minor additional constituents
						natural	natural calcined	siliceous	calcareous				
			K	S	D[(b)]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95 - 100	-	-	-	-	-	-	-	-	-	0 - 5
CEM II	Portland-slag cement	CEM II A-S	80 - 94	6 - 20	-	-	-	-	-	-	-	-	0 - 5
		CEM II B-S	65 - 79	21 - 35	-	-	-	-	-	-	-	-	0 - 5
	Portland-silica fume cement	CEM II A-D	90 - 94	-	6 - 10	-	-	-	-	-	-	-	0 - 5
	Portland-pozzolana cement	CEM II A-P	80 - 94	-	-	6 - 20	-	-	-	-	-	-	0 - 5
		CEM II B-P	65 - 79	-	-	21 - 35	-	-	-	-	-	-	0 - 5
		CEM II A-Q	80 - 94	-	-	-	6 - 20	-	-	-	-	-	0 - 5
		CEM II B-Q	65 - 79	-	-	-	21 - 35	-	-	-	-	-	0 - 5
	Portland-fly ash cement	CEM II A-V	80 - 94	-	-	-	-	6 - 20	-	-	-	-	0 - 5
		CEM II B-V	65 - 79	-	-	-	-	21 - 35	-	-	-	-	0 - 5
		CEM II A-W	80 - 94	-	-	-	-	-	6 - 20	-	-	-	0 - 5
		CEM II B-W	65 - 79	-	-	-	-	-	21 - 35	-	-	-	0 - 5
	Portland-burnt shale cement	CEM II A-T	80 - 94	-	-	-	-	-	-	6 - 20	-	-	0 - 5
		CEM II B-T	65 - 79	-	-	-	-	-	-	21 - 35	-	-	0 - 5
	Portland-limestone cement	CEM II A-L	80 - 94	-	-	-	-	-	-	-	6 - 20	-	0 - 5
		CEM II B-L	65 - 79	-	-	-	-	-	-	-	21 - 35	-	0 - 5
		CEM II A-LL	80 - 94	-	-	-	-	-	-	-	-	6 - 20	0 - 5
		CEM II B-LL	65 - 79	-	-	-	-	-	-	-	-	21 - 35	0 - 5
	Portland-composite cement[(c)]	CEM II A-M	80 - 94	◄------				6 - 20				------►	0 - 5
		CEM II B-M	65 - 79	◄------				21 - 35				------►	0 - 5
CEM III	Blastfurnace cement	CEM III A	35 - 64	36 - 65	-	-	-	-	-	-	-	-	0 - 5
		CEM III B	20 - 34	66 - 80	-	-	-	-	-	-	-	-	0 - 5
		CEM III C	5 - 19	81 - 95	-	-	-	-	-	-	-	-	0 - 5
CEM IV	Pozzolanic cement[(c)]	CEM IV A	65 - 89	-	◄------		11 - 35		------►	-	-	-	0 - 5
		CEM IV B	45 - 64	-	◄------		36 - 55		------►	-	-	-	0 - 5
CEM V	Composite cement[(c)]	CEM V A	40 - 64	18 - 30	-	◄------	18 - 30		------►	-	-	-	0 - 5
		CEM V B	20 - 39	31 - 50	-	◄------	31 - 50		------►	-	-	-	0 - 5

Notes

(a) The values in the table refer to the sum of the main and minor additional constituents.

(b) The proportion of silica fume is limited to 10%.

(c) In portland-composite cements CEM II A-M and CEM II B-M, in pozzolanic cements CEM IV A and CEM IV B, and in composite cements CEM V A and CEM V B, the main constituents other than clinker shall be declared by designation of the cement.

It is perceived that using FA can increase the strength gain of concrete over time due to the pozzolanic activity while the water content of the concrete can also be reduced by a minimum of 10 liters per cubic meter. The workability of the concrete can be improved at the same water content with reduced permeability thus improving the durability, with greater resistance to sulphate and chloride attack (Ash Resources, 2009: 9). The use of FA is more common in water retaining structures because it results in more impervious concrete than conventional concrete.

FA has been utilized successfully in many concrete projects globally. Even so, the specifications by SANS 50197-1 (2000), see Table 2.1, and majority of engineers still limit its usage as a cement extender in concrete (Cement and Concrete Institute, 2009).

Increasing the content of FA could prove to be very cost effective also in terms of materials cost and even handling the concrete on site. From an economic standpoint, HVFA mixes are cost competitive from a materials first cost basis. When a life cycle analysis is considered and/or if carbon trading becomes a reality worldwide, the cost savings of HVFA mixes may be even greater (Bentz et al., 2010: 7).

2.4 Properties of fly ash

The properties of FA vary with the mineral composition of coal used, the grinding equipment, the furnace and the combustion process of coal (Tharaniyil, 2013: 16). Table 2.2 shows the typical chemical composition of South African cements and FA's.

Table 2.2: Comparison between typical South African Portland Cement and FA properties (Ash Resources and PPC Cement, n.d.).

Chemical Composition and Physical Properties	Portland Cement	FA
Silicon (SiO_2) (%)	19 - 24	45 - 65
Aluminium (Al_2O_3) (%)	4 - 7	25 - 35
Iron (Fe_2O_3) (%)	1 - 4	3 - 5
Calcium (CaO) total (%)	63 - 68	4 - 7
Magnesium (MgO) (%)	0,5 – 3,5	0,5 - 2
Sulphur (SO_3) (%)	2	0,22 – 1,04
Cl^{-1} (%)	0,01	0,00 – 0,06
Free CaO (%)	0,5 – 2,5	0,00 – 0,12
Loss On Ignition (LOI) (%)	2,5	0,8 – 2,5
Insoluble residue (%)	2	-
Specific weight (kg/m^3)	3140	2120 - 2200
Blaine specific area (m^2/kg)	400	-
Fineness (%)	1,7 (> 90 µm)	14,1 – 31,6 (> 45 µm)
Water demand (%)	28,0	30,0

2.4.1 Chemical properties of fly ash

FA is classified globally by ASTM and SANS as either Class C or Class F, according to their aggregate Alumina (AlO), Silica (SiO) and Ferric Oxide (FeO) contents. South African FA is classified as Class F (Heyns and Hassan, 2014). Class F FA is pozzolanic, with little or no cementing value, while Class C FA has both pozzolanic and self-cementing properties (Federal Highway Administration, 2016). FA's differ from each other mainly in terms of calcium content. Class F FA contains less than 10 percent CaO and is a product of the combustion of anthracite and bituminous coals. Class C ashes are considered calcareous ashes and usually contain more than 10 percent CaO. These ashes are mainly produced from sub-bituminous or lignite coals. The main criterions for classification are the chemical requirements, which can be expressed as follows:

- SiO2 + Al2O3 + Fe2O3 > 70% for Class F and
- SiO2 + Al2O3 + Fe2O3 > 50% for Class C (Burden, 2006: 1).

FA is primarily silicate glass containing large amounts of silica, alumina, iron, and calcium, with minor constituents being magnesium, sulphur, sodium, potassium, and carbon. There are also small amounts of crystalline compounds present. The principal crystalline materials of low-calcium FA are quartz, mullite and hematite or magnetite. The presence, in large quantities, of the materials tends to reduce the reactivity of FA, due to being non-reactive at ordinary temperatures. Class C FA is in general more reactive as it contains more calcium in the form of reactive crystalline compounds (Kearsley and Wainwright, 2003: 19). The carbon content in FA is a result of incomplete combustion of the coal and organic additives used in the collection process. Carbon content is not usually determined directly, but is often assumed to be approximately equal to the loss on ignition (LOI) (ACI Committee 232, 2002). Other chemical requirements specified in the ASTM C618 specification (for both Class C and Class F FA) include sulfur trioxide content (5.0% maximum), moisture content (3.0% maximum), and LOI (6.0% maximum), (Bentz, Ferraris and Snyder, 2013: 5)

LOI is a very important factor for determining the quality of FA for use in concrete as it primarily represents residual carbonaceous material that may impact negatively on the usage of FA in air-entrained concrete. FA's used in concrete typically have LOI level less than 6 percent (ACI Committee 232, 2002). FA with LOI greater than 3 percent usually increase the water demand in concrete and that can result in loss of strength due to higher water content (Feng and Clark, 2011). In a study by Atis (2005:1115), it was found that between Drax FA and Aberthaw FA's, Drax FA had a capacity to reduce the water demand of a concrete mix, while Aberthaw FA increased it due to its high LOI value. This resulted to Drax FA concrete developing higher strength than Aberthaw FA concrete. FA with low and consistent LOI value is desirable for minimizing the quantity of air-entraining admixture to produce durable concrete (Tharaniyil, 2013: 17).

2.4.2 Physical properties fly ash

FA is a finely divided gray powder that resembles cement. It has a surface area ranging from about 200 m^2/kg to 500 m^2/kg, and a typical relative density (specific gravity) ranging between 1,9 and 2,8 (Kosmatka, Kerkhoff and Panarese, 2003: 58). FA is characterized in two categories in terms of fineness, SANS 50450-1:2014 (2014) specifies that:

- **For Category N**; the retained residue on a 45-μm screen shall not exceed 40% by mass and
- **For Category S**; the retained residue shall not exceed 12% by mass.

FA particle sizes vary from less than one micrometer (μm) to more than 100 μm, with the typical particle size measuring less than 20 μm. About 10 percent to 30% of the particles by mass are larger than 45 μm (Kosmatka, Kerkhoff and Panarese, 2003: 58). In comparison, the typical particle size distribution of PC ranges up to 100 μm with a mean particle size of 35 μm and classified South African FA has a mean particle size of 25 μm.

FA particles are predominantly spherical in shape (see Figure 2.1) in contrast to PC particles, which are angular (Ash Resources, 2009: 9). Most of FA particles are solid spheres and some are hollow cenospheres. Also present are plerospheres, which are spheres containing smaller spheres (Kosmatka, Kerkhoff and Panarese, 2003: 58).

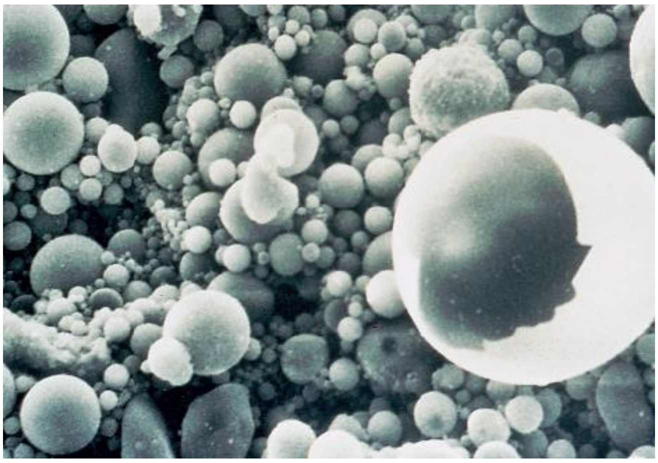


Figure 2.1: Micrograph showing spherical FA particle (Thomas, 2007: 2).

The spherical shape enables FA to flow and blend easily in a concrete mix (Ash Resources, 2009: 8). Also the particle sizes of FA can affect the strength gain of concrete. In a study by Erdogdu and Turker (1998: 1219), when comparing the strength gain of high-lime and low-lime FA's, they found that the finer the fraction of FA used, the higher the compressive strength the tests yielded. They noted that the changes in strength differences were due to the particles size difference between the size fractions used. Particles sizes above the 0,300 mm sieve are considered inert, as they do not participate in pozzolanic reactions and particles between the 0,010 mm and the 0,300 mm sieve are the ones that slowly react (Heyns and Hassan, 2014).

2.4.3 Pozzolanic properties of fly ash

Both Class C and Class F are pozzolans. The most important factors that affect the pozzolanic reactivity of FA are fineness, glass content and acid oxide content (SiO_2 + Al_2O_3 + Fe_2O_3), (Feng and Clark, 2011). During the pozzolanic activity the FA reacts chemically with free lime to create more C-S-H, the same "glue" produced by the hydration of cement and water, thereby closing off the capillaries that allow the movement of moisture through the concrete (Headwaters Resources, 2014: 06).

The formation C-S-H through the hydration and pozzolanic reactions happens as follows (Jeong and Lee, 2010: 252);

- $2(3CaO \cdot SiO_2) + 6H_2O \rightarrow 3CaO \cdot 2SiO_2.3H_2O + 3Ca(OH)_2$ (primary C-S-H)
- $3Ca(OH)_2 + 2SiO_2 + H2O \rightarrow 3CaO.2SiO_2.3H2O + 3Ca(OH)_2$ (secondary C-S-H)

The pozzolanic reactions are primary reactions of FA in cement, with respect to the PC hydration reactionand they are much slower reactions which occur after one or two weeks (Ma and Brown, 1997 cited in Ćojbašić et al., 2005: 117). The reaction occures when there is enough $Ca(OH)_2$ to be absorbed in the system. If the content of FA is increased, the pozzolanic reaction of FA is slowed because the promotion of cement weakens (Wang, Zhang and Su, 2004). The sum of reactive silica and alumina in the FA indicate the pozzolanic activity of the FA (NTPC Limited, 2007: 12).

Studies have shown the pozzolanic reaction on FA being effective around 90 days and beyond, where the mechanical and durability properties of the concrete show considerable improvement (Bouzoubaâ et al., 2001, Burden, 2006, Liu et al., 2014, Bouzoubaâ, Zhang and Malhotra, 1999 and Atis 2005). The pozzolanic reaction is more dominant at the time of 180-days while the water dissolution becomes more evident after 270 days (Liu et al., 2014: 4293).

Curing temperature is related to pozzolanic ratio and strength development, as the temperature rises, the pozzolanic ratio rises. At ambient temperatures the pozzolanic ratio is at about 70%, however at 90°C - 200°C the pozzolanic ratio can rise up to 90% (Jeong and Lee, 2010: 252).

2.5 Effects of fly ash on concrete properties

FA has a great potential of improving concrete properties when compared to ordinary concrete mixes. Many studies have shown that FA improves most properties of green and hardened concrete. Properties such as concrete compressive strength and durability are the most important to look at as engineers use these for specifying the criteria of concrete to be used as per SANS 50206:2015 (2015) specifications. Other concrete properties also play an important role in ensuring that the desired performance of concrete is achieved.

2.5.1 Influence of fly ash on plastic properties of concrete

The rheological properties of concrete are influenced by the composition of the mixture, which include the type and particle size distribution (PSD) of cement, SCMs' type and PSD, shape and PSD of aggregates, W/CM ratio, chemical admixtures and air content (Bentz, Ferraris and Snyder, 2013: 17). Mineral admixtures such as blast furnace slag, FA and silica fumes have been used in order to increase strength and improve durability and flowability of cementitious material (Park, Noh and Park, 2005: 842).

FA is known for influencing the rheological properties of plastic concrete by providing better concrete compaction and dependable workability retention. FA can also affect the cohesiveness, workability, bleeding, and shrinkage of concrete positively (Headwaters Resources, 2014: 9-10).

a. Concrete workability

Workability is defined by ACI as "that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition". The workability of conventional concrete is usually measured or specified by slump. (Bentz, Ferraris and Snyder, 2013: 17). The physical properties of FA provide great assistance in working with fresh concrete, where the spherical shape of the FA particles improves the workability of concrete. The greater the percentage of FA in the concrete paste, the better the lubrication of aggregates and the better the flow of concrete due to the "ball bearing effect" of FA particles (Headwaters Resources, 2014: 07).

The use of good quality FA with a high fineness and low carbon content tends to reduce the water demand of concrete and improves the cohesiveness of concrete (Thomas, 2007: 4). Research has shown that for low W/CM HVFA mixes, an increased dosage of super-plasticizers is required for a slump and air content equal to conventional concrete, due to less water demand (Bouzoubaâ et al., 2001: 12). A study by Ganesh and Amarnath (2012) proved that it is possible to obtain workable (low vebe compaction time) roller compacted concrete (RCC) even at very low cement content with very high volumes of FA. They found that for nearly the same workable and fully compactable RCCs, increases in cementitious materials decrease the required W/CM ratio. Bouzoubaa et al., 2007 investigated the use of 30%, 40%, and 50% by mass replacement of cement with FA. They found that as FA content increased, the water requirement to attain a given slump decreased, and consequently the water-to-cementitious material ratio (W/CM) decreased as well (Bouzoubaa et al., 2007 cited in Davis, 2012: 10). Kearsley and Wainwright (2003) investigated thirty-four FA's from nineteen different sources and noted that the water requirement for the different FA's was considered to be a function of the carbon content of the FA; the higher the carbon content the higher the water demand.

b. Air content

Introducing air into concrete mixes affects the characteristics of both plastic and hardened concrete. In fresh concrete, the tiny air bubbles act as a lubricant thus improving the workability and increasing the slump. In hardened concrete, air entrainment can provide enhanced weather-ability and improved resistance to scaling (The Aberdeen Group, 1976). However if the air is entrapped in concrete, then water and sulphate penetration as well as stress concentrations in the mortar can also occur (Esplin, 2012: 1).

The materials used to produce concrete; cement, supplementary cementitious materials, chemical admixes, aggregates, and mixing water, can have a significant effect on air content (Portland Cement Association, 1998: 3). Finely divided materials may tend to reduce the entrained air content of concrete. Hence, if FA or natural pozzolan is added to any concrete for which entrainment of air is specified, provision should be made to ensure that the specified air content is maintained by air content tests and by use of additional air-entraining admix or use of an air-entraining admix in combination with air-entraining hydraulic cement (ASTM C618-15, 2015).
The effectiveness of air entraining admixtures decreases with increase in FA content to cementitious content ratio. Higher content of air entraining admix has to be used when the carbon content in the FA is higher (Madhavi, Raju and Mathur, 2014: 8). A study by Bilodeau, Malhotra and Seabrook (2001), they noted that the characteristics of the FA and cement used strongly influenced the dosage of the air-entraining admixture. Higher dosages of air-entraining admixture were needed for FA having very high carbon content (Bilodeau, Malhotra and Seabrook, 2001). Class C FA's with significant water-soluble alkalis can reduce the amount of air-entraining admix required (Pistilli, 1983 cited in ACI Committee 232, 2002: 10).

Great benefits can be obtained when using more completely consolidating FA concrete in areas of difficult placement, such as over-reinforced concrete, where rock pockets and other concrete placing defects often occur (Headwaters Resources, 2014: 09). In some special projects, concrete with 60% FA was used successfully in the construction on thin walls for a Madera housing project in Gainesville, Florida. Due to high slumps needed for concrete to flow through insulating concrete forms, a 60% FA concrete was recommended (Headwaters Resources, 2005c).

c. Bleeding of concrete

In most applications, FA reduces the bleeding of concrete, including both the amount and rate of bleeding. This effect will vary with the type of FA used and will be influenced by overall concrete mix proportions and characteristics (Electric Power Research Institute, 2007: 2-2). Concretes that incorporate HVFA generally exhibit less bleeding and segregation than conventional concretes due to the high volume of fines and a low water content (Kosmatka, Kerkhoff and Panarese, 2003: 62 and Mehta, 2004: 11). However, the reduction in bleeding can be problematic in hot, dry, windy conditions, where it can lead to plastic shrinkage cracking, and this can be exacerbated when FA is used in relatively high dosages, where bleeding is further reduced and setting is prolonged, as it can slow down the early-age tensile strength gain (Electric Power Research Institute, 2007: 2-2).

For HVFA concrete, the bleeding ranges from being very low to negligible due to lower water content, so it is recommended that moist curing should commence immediately after placing the concrete to prevent plastic shrinkage at the concrete surface (Bilodeau and Malhotra, 1998).

d. Setting of concrete

Setting can be defined as the transitioning of concrete from the plastic state into a rigid state. It happens gradually over a period of hours until concrete gets hard. Setting is different from hardening, which describes the development of concrete strength. Setting precedes hardening and they are both controlled by the hydration of the cement. The setting behavior of concrete is important to construction operations, such as placing and removal of formwork. If the initial set time is short, there might not be sufficient time to work with concrete, while a prolonged final set time may delay the removal of formwork. (Hou, 2013: 22)

The effects of Class C FA and Class F FA on concrete setting time are not all similar, generally Class F FA increases the setting time of concrete (Hou, 2013: 9). Higher-calcium FA's generally retard setting to a lesser degree than low-calcium FAs, probably because the hydraulic reactivity of FA increases with increasing calcium content (Thomas, 2007: 6). When studying the properties of HVFA concretes, Bouzoubaâ et al. (2001: 8) found that the initial and final setting times of the concrete made with the

HVFA blended cements were 1 h:50 min to 2 h:30 min longer than those of the control concrete.

When designing HVFA concrete, one should ensure that the cement, FA and other chemicals and admixtures are compatible, to avoid improper combination of materials that can lead to flash or delayed setting. Delayed setting is due to excessive retardation of the hydration reactions (Bentz, Ferraris and Snyder, 2013: 10). The impact of FA on the setting behavior of concrete is not only dependent on the composition and quantity of FA used, but also on the type and amount of cement, the W/CM, the type and amount of chemical admixes and the concrete temperature. In a study by Zang, Zakaria and Islam (2012), they found that the incorporation of 2% nano-silica reduced the initial and final setting times of the FA concrete by 90 min and 100 min respectively.

Setting characteristics of concrete are greatly affected by the weather. Cold weather and lower concrete temperatures threaten to slow down the rate of setting, and hot weather and warm concrete cause concrete to set faster. During cold weather, the use of FA, especially at high levels of replacement, can lead to very significant delays in both the initial and final set. The use of FA in cold weather concreting has been successfully accomplished by adjusting the mix by using rapid setting Type III PC, and by adding liquid admixtures such as calcium chloride, non-chloride accelerators, and mid-range water reducers (Headwaters Resources, 2005e and Bentz, Ferraris and Snyder, 2013).

e. Heat of hydration

The hydration of cement is an exothermic reaction, when heat is generated very quickly, thus causing the concrete temperature to rise and accelerating the setting time and strength gain of the concrete (Headwaters Resources, 2014: 08). When partially replacing PC with FA, the hydration between cement and water is reduced. It is estimated that the contribution of FA to early age heat generation ranges from 15% to 30% of that of an equivalent mass of Portland cement (Berry and Malhotra, 1986: 33). In a study by Bouzoubaâ et al., 2001: 12, they found that the maximum temperature reached in concrete made with HVFA blended cement was 34°C compared to 52°C for control concrete. Values of heat of reaction of some South African cement types are shown in Table 2.3. It can be seen that the use of FA and GBFS lowers the heat of reaction (Taylor and Addis, 1994a: 92).

Table 2.3: Heat of reaction at different ages (Taylor and Addis, 1994a: 92).

Cement type	Approximate heat of reaction under adiabatic conditions (kJ/kg)		
	3 days	**5 days**	**7 days**
OPC	250	280	300
RHPC	350	360	300
85% OPC + 15% GGBS	240	270	290
70% OPC + 30% GGBS	220	260	280
50% OPC + 50% GGBS	190	240	260
30% OPC + 70% GGBS	150	190	210
85% OPC + 15% FA	230	250	270
70% OPC + 30% FA	200	220	240

It is perceived that the rate of pozzolanic reaction is slower than the rate of hydration, therefore partial replacement of PC with FA results in a release of heat over a longer period and the concrete temperature remains lower because heat is dissipated as it is produced (Joshi and Lohtia, 1997: 84). During the critical first 24 hours, replacement of about 45 kg of cement with the same amount of FA can reduce the heat of hydration by 19 percent, without sacrificing any strength or durability features. The damaging effects that are caused by an increased rate of hydration can be reduced by replacing large percentages of cement with FA (Headwaters Resources, 2005d).

A study conducted by Langan, Weng and Ward (2002) found that as the W/CM ratio increases, the retarding effect of FA increases. Therefore, the addition of FA accelerates hydration in the first few minutes, reduces hydration in the dormant periods of low heat evolution, which is then followed by accelerated hydration. FA is believed to be inert at this very early stage. Its effect on the 24-hour hydration seems to be the result of a change in the amount of water available for cement hydration and the different mechanisms at the different stages of hydration.

Temperature has a big effect on the hydration process. When studying the effect of FA on the kinetics of PC hydration at different curing, Narmluk and Nawa (2011) found that the effect of FA on the hydration of cement is dependent on the curing temperature and the FA replacement ratio. At common curing temperatures, between 20°C and 35°C, FA retards the hydration at early periods but at later periods, the hydration of cement is accelerated. They observed that at higher curing temperatures (50°C) and high FA replacement ratios, the FA retards the hydration of cement at later stages due the pozzolanic reaction of FA as it competes with the cement hydration in consuming water; as a result, the hydration is impeded (Narmluk and Nawa, 2011).

Although most low calcium FAs (Class F) will reduce the rate of temperature rise when used as cement replacement, high calcium FAs (Class C) react rapidly with water, just as normal PC hydration, because of their self-cementitious properties (Joshi and Lohtia, 1997: 85). In massive concrete pours where the rate of heat loss is small, the maximum temperature rise in FA concrete will primarily be a function of the amount and composition of the PC and FA used, together with the temperature of the concrete at the time of placing. Concrete with low PC contents and high FA contents are particularly suitable for minimizing autogenous temperature rises (Thomas, 2007: 6).

In general, the rate of heat evolution parallels the rate of strength development. Some high calcium ashes react very rapidly with water, generating excessive heat rather than reducing the heat of hydration (Berry and Malhotra, 1986: 37). This can result in slower early strength development under normal curing temperatures. If the concrete is moist cured or exposed to sufficient moisture during service, FA concrete with equivalent or lower strength at early ages may have equivalent or higher strength at later ages than ordinary concrete without FA. (Burden, 2006: 12).

2.5.2 Effects of fly ash on mechanical properties of concrete

The properties of HVFA concrete are strongly dependent on the characteristics of the cement and FA used (Bilodeau and Malhotra, 1998: 6). FA is known to affect the concrete strength gain over time, while providing better aesthetics with smoother off-shutter finishes (Ash Resources, 2009: 9). The relationships between tensile strength, flexural strength, elastic modulus and the compressive strength of concrete are not significantly affected by the presence of FA at low and moderate levels of replacement (Malhotra and Mehta (2002) cited in Thomas, 2007: 9). In general, the mechanical properties of concrete with high content of FA are considered excellent, due to low water content and dense microstructure (Bilodeau and Malhotra, 1998: 6).

a. Compressive strength

The strength of hardened concrete is of fundamental importance to structural designers. It is extensively used as an index of other concrete properties and of concrete quality (Addis, 1994b: 97). Strength is defined as the ability of a material to resist stress without failure. Structural design and specifications generally refer to 28-days compressive strength, however early strength test results such as the 7-days compressive strength test results may be used to predict 28-days results (Holcim SA, 2006: 143). The prediction of concrete strength before its placement allows engineers to improve planning and quality control. Moreover, a well-defined concrete strength prediction can save time, accelerating the overall construction (Martins and Camões, 2013: 3). The compressive strength of concrete one to three days after placing is important for structures where early loading is expected, fast-track construction is required or stripping of shutters is necessary (Holcim SA, 2006: 143).

The rate of strength development at early ages is related to the rate of hydration of cement (National Ready Mixed Concrete Association, 2006). Strength gain contributed by PC occurs very rapidly at early ages up to about seven days, after which it slows markedly.The partial substitution of cement with FA is believed to have positive effects in hardened concrete as it promotes higher strength gain and concrete that is more durable. However, the use of FA in concrete has been proven to reduce early strength (up to 28 days) and improve the ultimate strength, even after more than a year. Strength development contributed by FA occurs through the pozzolanic activity (Headwaters Resources, 2005a). The pozzolanic reaction has a more significant impact on the long-term strength and less significant impact on the early strength as adding SCMs to the binder has a similar effect as raising the dicalcium silicate (C_2S) compound in cement, which contributes to the final strength of concrete (Hannesson, 2011: 4).

Studies have demonstrated that high calcium FA (Class C) will show a more rapid strength gain at early ages than concrete made with a lower calcium FA (Class F) because Class C ashes often exhibit a higher rate of reaction at early ages than Class F ashes. However, Class F ashes will contribute to greater long-term strength gain of concrete than Class C ashes in spite of its slower rate of strength development at early age (Burden, 2006: 12). In a study by Papadakis (2000: 1653), it was observed that when high calcium replaces PC, the final strength exceeded that of the control mix only if the content of active silica in the fly ash is higher than that in the cement. The final strength gain was roughly proportional to the content of active silica in the mortar volume.

HVFA mixtures have been recorded continuing to develop significant additional strength beyond 28 days, it is thus more likely that the HVFA mixtures can be employed in practice if the compliance testing can be postponed to 56-days or even 91-days (Bentz, Ferraris and Snyder, 2013: 29). When evaluating the sustainability of high-volume FA concretes, Durán-Herrera et al. (2011: 43) found that as the FA content increased the compressive strength decreased, and also with age, the difference between the compressive strength of the concretes with FA and the reference concretes tended to decrease as a result of the pozzolanic activity of the FA. In their study on HVFA blended cements in concrete, Bouzoubaâ, Zhang and Malhotra (1999) found that the compressive strength at 1, 7, 28, and 91 days of the concrete made with the HVFA blended cements represented 45%, 85%, 100%, and 125% of the compressive strength of the concrete made with normal PC respectively.

There is usually a concern within the construction industry regarding the slow gain of concrete strength at early stages for FA concrete, especially where post tensioning is required. Although FA seems to reduce the setting time and early strength, the additions of accelerators, plasticisers and sometimes small amounts of additional condensed silica fumes can mitigate this problem (Rosenberg, 2010). The compressive strength of HVFA mixes can be enhanced by including different chemical activators such as 3%–5% sulphate and 3% $CaCl_2$ to accelerate the hydration (Rashad, 2015: 303). Utilizing Type III cements can also provide a significant boost to the early age strengths of HVFA concrete mixtures. EcoSmart's various case studies have resulted in positive information regarding early age strength of HVFA concrete, the experience from field mixes is that high volume FA concrete did not show unacceptable retardation in initial setting time, and demonstrated enough strength development, to produce adequate strength at one day (Gilies, 2001: 10).

b. Flexural and splitting tensile strengths

Flexural tensile strength is of utmost significance in the construction of concrete slabs and beams as they are subjected to tensile stresses due to bending action (Atis, 2005: 1116). Available literature shows that the flexural and splitting-tensile strengths of FA concrete tend to follow the trend of compressive strength i.e. being lower at early ages and higher at later ages for a given specified strength (Electric Power Research

Institute, 2007: 3-2). A study by Atis (2005: 1116) found that at early curing days, the flexural tensile strengths of the 70% FA mixes was lower that of control OPC concrete, while the flexural tensile strengths of the 50% FA mixes were comparable or higher than the strength of the control OPC mixes. After three months of curing, the 70% FA mixes attained comparable flexural tensile strength to the corresponding control concrete. In addition, the splitting tensile strength of concrete containing 50% FA was higher than that of the 70% FA mixes.

In a study by Davis (2012: 103), it was observed that at 50% replacement there was relatively little change in flexural and splitting tensile strength, and at 70% replacement, the mixes exhibited lowered flexural and splitting tensile strength. Malhotra and Mehta, 2005 cited in Thomas, (2007: 9) suggested that the long-term flexural and tensile strength of HVFA concrete might be much improved due to the continuing pozzolanic reaction strengthening the bond between paste and the aggregate.

c. *Young's Modulus of Elasticity "E"*

Similar to flexural and splitting-tensile strengths, the relationship between the Young's Modulus of Elasticity and compressive strength is not significantly affected by conventional amounts of FA in the concrete. In general, the modulus of elasticity of FA concrete will follow a similar trend as that of compressive and other strength properties (Electric Power Research Institute, 2007: 3-2).

In a study by Davis (2012: 103) the Young's modulus of elasticity benefitted from FA replacement in terms of mechanical properties, with 50% FA resulting in a similar or noticeably stiffer end product. The 70% FA replacement of cement resulted in slightly lowered moduli of elasticity, but within still in a reasonable range. In a study by Bilodeau and Malhotra (1998: 7), they suggested that the high elastic modulus achieved for HVFA concrete was due to the presence of significant amounts of unreacted FA particles, consisting of glassy spherical particles, which act as fine aggregate.

d. *Drying shrinkage*

When concrete dries and sets under normal atmospheric condition it shrinks. This is a result of water loss due to hydration of cement. Drying shrinkage occurs after hardening of concrete, where the water that was not consumed by cement leaves the system (Scott and Tarr, 2008). Drying shrinkage is a long-term process that typically occurs over a period of up to 30 years (Holcim SA, 2006: 152). One of the most substantial factors influencing the free shrinkage is the W/CM ratio. It is said that concrete specimens with lower W/CM ratios have lower amounts of pore water and consequently exhibit lower drying shrinkage (Tia et al., 2005: 5). High cement content tends to increase the shrinkage of concrete due to higher rate of hydration. Other factors that can influence shrinkage include chemical admixes, mineral admixes, cement composition and types and size of aggregates used, since they typically alter the reaction products, porosity and mechanical stiffness (Powers and Brownyard, 1948 cited in Tia et al., 2005: 6).

FA used in mortar reduces the drying shrinkages by 30% to 40% (Tia et al., 2005: 10). Borsoi et al. (2009) found that there is a significant reduction (20% at 120 days of exposure to relative humidity of 50%) in the unrestrained drying shrinkage of concretes when PC is replaced by 20% of FA. Kate and Murnal (2013: 15) found that the shrinkage of high strength concrete increases with an increase in FA content, and the rate of increase of shrinkage with time is uniform for low FA content, whereas it generally increases after 28 days for HVFA.

It has been reported that the drying shrinkage of HVFA concrete is generally less than conventional concrete. In their study, Bouzoubaâ, Zhang and Malhotra (1999) found that the drying shrinkage strains of the concrete made with the HVFA blended cement were comparable to, or lower than that of the concrete made with PC only. After 32 weeks of exposure to dry air, they measured values in the order of 500×10^{-6} mm/mm. Rivest, Bouzoubaa and Malhotra, (2004) cited in Davis (2012: 21), recorded shrinkage strains out to one year for the HVFA concrete mix as well as control mixes made with Type I and Type II cement, as specified by ASTM C595. The authors found that the control concretes showed more shrinkage (strains of 0.069 mm/mm and 0.059 mm/mm respectively) compared to the HVFA concrete, which showed a strain of only 0.048 mm/mm. They suggested that this was due to the lower water content requirement of HVFA concretes, as well as greater unhydrated cementitious material in the HVFA mix, which serves to act as aggregate, thus restraining shrinkage.
Quan and Kasami (2014: 9) did a study on the durability Improvement of FA concrete with durability improving admixes and they found that using durability improving admix in FA concrete, reduced drying shrinkage by 60%. This can be attributed to the reduced amount of water required due to the addition of admixes.

2.5.3 The effects of fly ash on concrete durability

When specifying for concrete durability, engineers should not rely solely on specifying a minimum compressive strength, maximum W/CM ratio, minimum cementitious content and air entrainment. Low permeability and shrinkage are two performance characteristics of concrete that can prolong the service life of a structure that is subjected to severe exposure conditions (Obla, Lobo, and Lemay, 2006: 43). Most deterioration processes involve two stages. Initially, aggressive agents (water or solutions with dissolved solids or gases) need to penetrate or be transported through the capillary pore structure of the concrete to reaction sites (e.g. chlorides penetrating to metallic reinforcement, sulphates penetrating to reactive aluminates) prior to the actual chemical or physical deterioration reactions (Bickley, Hooton and Hover, 2006; 3-5).

a. Permeability

Permeability is the most important aspect of concrete durability. To be durable, concrete must be relatively impervious (Berry and Malhotra, 1986: 89). In general, lower permeability means greater durability. Permeability of concrete is governed by many factors such as amount of cementitious material, water content, aggregate grading, consolidation, and curing efficiency (ACI Committee 232, 2002: 14).

The incorporation of FA can result in considerable pore refinement, which is a transformation of bigger pores into smaller ones due to the formation of pozzolanic reaction products concomitant with the progress of cement hydration (Joshi and Lohtia, 1997: 112). Due to the pozzolanic reaction between FA and lime, the permeability of concrete is considerably reduced thereby decreasing the ingress of moisture, oxygen, CO_2, chlorides and other harmful agents that affect the durability of concrete (Joshi and Lohtia, 1997: 150). FA concrete is considered less permeable because through pozzolanic activity, FA creates more durable C-S-H as it fills capillaries and bleed water channels occupied by water-soluble lime (Headwaters Resources, 2014: 08). Studies have shown that after six months of curing, FA concretes are much less permeable than OPC concretes due to the slow pozzolanic reaction of FA (Burden, 2006: 14).

b. Chloride conductivity

Testing for chloride conductivity is related to chloride ingress into concrete (Alexander, Mackechnie and Ballim, 1999). Chloride conductivity is said to decrease with the addition of FA in concrete. FA reduces the chloride ingress as chlorides chemically bind to the FA due to the high aluminate content, which is about three to five times higher than in cement (Ash Resources, 2011:6). Figure 2.2 shows a typical results measured at 28 days for OPC, FA and slag concretes. These results show that the addition of FA and slag decreases the Chloride Conductivity compared to OPC concrete.

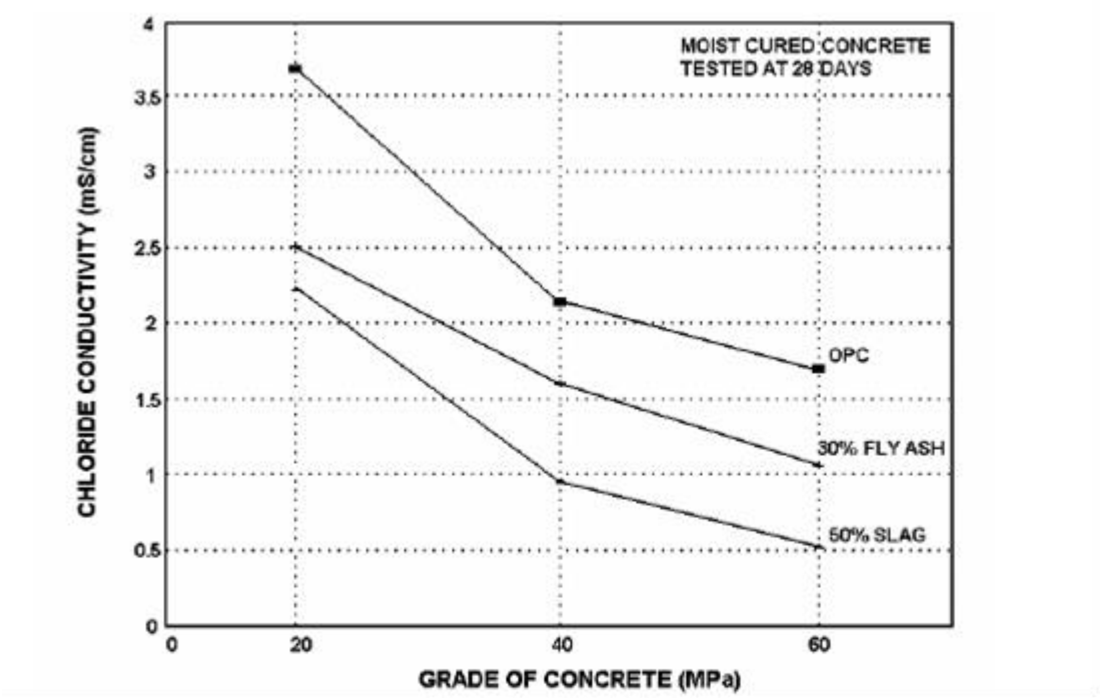


Figure 2.2: Typical Chloride Conductivity results (Alexander, Mackechnie and Ballim, 1999).

In a study conducted by Balakrishnan and Awal (2014: 532), when comparing non-FA concrete to FA concrete, they observed that concrete without FA had suffered the most deterioration in all the three chemical solutions, with the non-FA concrete having the highest chloride penetration while HVFA concrete had more than 50% lower penetration at 90-days. In a study by Gu et al., (1999: 558) they examined the performance of steel reinforcement in HVFA concretes when exposed to chloride solutions. Two HVFA mixes in this study incorporated 58% by mass as a cement replacement, one containing Class F FA, and one with Class C FA. The authors noted greater resistance to chloride ion permeability than the control concretes, made with PC, even at only 28-days of age.

Yu and Ye (2012:) studied the chloride penetration and microstructure development of FA concrete and the test results showed that FA concrete has good resistance to chloride ions after the curing age of 28-days compared to OPC concrete. Nath and Sarker (2011) conducted a study on the effect of FA on the durability properties of high strength concrete and found that the inclusion of FA reduced sorptivity and chloride ion permeation significantly at 28-days which reduced further at six months. In their study, Bouzoubaâ et al. (2001) found that at 91-days of curing, the concrete with blended cements had higher resistance (< 700 coulombs) to the chloride ion penetration than the control concrete (4000 coulombs). This was due to the fact that the incorporation of the FA in the blended cement results in finer pores in the hydrated cement paste.

Using HVFA concrete can be very beneficial in reinforced concrete structures that built in moist environments. Chalee, Ausapanit and Jaturapitakkul (2010) found that the increase of FA replacement in concrete clearly reduced the chloride ion penetration, chloride ion penetration coefficient, and steel corrosion in concrete. Kayali and Ahmed (2013) conducted a study focusing on the realistic conditions of concrete making on site and the effects on the mechanical aspects as well as the consequences on corrosion of reinforcement. The study found that Class F FA may replace 50% of the PC and at the same time result in improving resistance to chloride ion initiated corrosion.

c. Sulphate resistance

The resistance of a reinforced concrete structure to corrosion, alkali aggregate expansion, sulphate and other forms of chemical attack depends on the water tightness of the concrete. In general, Class F FA can improve the sulphate resistance of concrete mixtures. The increase in sulphate resistance might to be due in part to the continued reaction of FA with hydroxides in concrete, continuing to form additional C-S-H, which fills in capillary pores in the cement paste, thus reducing permeability and the ingress of sulphate solutions (ACI Committee 232, 2002).

When properly cured, HVFA concrete is able to provide excellent water-tightness and durability (Mehta, 2004: 10). Class F ashes usually produce concrete that is generally more sulphate resistant than Class C ashes. Some Class C ashes have been known to reduce sulfate resistance at normal dosage rates (Kosmatka, Kerkhoff and Panarese, 2003: 69). In a study commissioned by Ash Resources in South Africa, they found that the inclusion of FA in concrete considerably increases its sulphate resistance, when used with OPC or Rapid Hardening Portland Cement (RHPC). This effect increases with FA content and at 50% FA, concrete attains resistance almost equal to a corresponding Sulphate Resisting Portland Cement (SRPC) concrete (Basson and Ballim, 1994: 156). In a study by Von Fay (1995: 10), it was found that increasing the FA to more than 50% provided more resistance to sulphate attack, with Class F FA being the most effective.

The sulfate resistance of FA concrete is influenced by the same factors which affect concrete without FA; the physical environmental conditions, curing and W/CM ratio, and will be dependent upon the class, amounts, and the individual chemical and physical characteristics of the FA and cement used (ACI Committee 232, 2002).

d. Carbonation

Carbonation occurs as a result of the hydration that occurs between hydrated cement and carbon dioxide in the atmosphere, which causes the concrete to shrink. Carbonation shrinkage occurs along the surface of concrete and as such it is usually not a main cause for concern in structural concrete (Tia et al., 2005: 5). Carbonation resistance of concrete is roughly proportional to W/CM ratio regardless of FA replacement ratio (Quan and Kasami, 2014: 9). Carbonation in concrete may result in increased permeability, increased shrinkage and cracking, and the reduction of the passive layer which protects reinforcing steel from corrosion (Berry and Malhotra, 1986: 93). The incorporation of FA in concrete may influence alkalinity, permeability and carbonation of the concrete cover surrounding the reinforcing steel (Joshi and Lohtia, 1997: 149).

The depth of carbonation is a function of the cement content for concretes moist-cured for 7 days, however, with a further curing to 90 days, concrete with FA showed a slower rate of carbonation as compared to plain and water-reduced concretes (Berry and Malhotra, 1986: 100). In his research, Burden (2006: 56) found that at 90 days of exposure in the accelerated carbonation chamber, concrete without FA yielded lower amounts of carbonation than concrete containing FA. Also, the following trends were clearly displayed: increased FA levels, increased W/CM, and decreased moist curing duration all increased carbonation depths. The replacement of PC by mineral additions at a given W/CM ratio increases the carbonation rate, with negligible difference at lower levels (15%) of replacement, however if the strength level is not reduced, there is no risk of corrosion promoted by carbonation in concretes containing FA and slag (Collepardi et al., n.d.).

When studying the relationship between carbonation reaction and pozzolanic reaction in FA concrete, Zhang, Cai and Shao (2016) found that pozzolanic reaction of FA in a FA-OPC system was hindered by early carbonation reaction. The higher the early carbonation degree, the lower was the pozzolanic reaction of FA. This could be due to both reactions competing for $Ca(OH)_2$.

In general, incorporation of FA as partial replacement of cement improved the durability properties of concrete. Nath and Sarker (2011) concluded that it is possible to design high strength concrete of reduced permeability by including up to 40 percent Class F FA in the total binder.

2.6 Conclusion

Studies that have been conducted on concrete with FA as a partial substitute have shown that there many benefits associated with increasing the amount of FA in concrete, and this practice could go a long way in alleviating some of the problems or factors that affect our environment and promote sustainable development.

This chapter has discussed global research and case studies where the practice of using HVFA provides benefits, technically and economically, without compromising the integrity of concrete structures or elements. The following chapters deal with the testing of high FA content concrete in South Africa, using tests that are relevant and available in the industry.

CHAPTER 3

3 LABORATORY WORK

3.1 Introduction

There are many different methods and types of concrete tests that can determine the performance of concrete structures, be it in the laboratory or outside environment. The results that can be obtained for two similar tests can vary widely due to factors such as materials, the methods used and the environment. This chapter looks at the methodology, materials used and the tests performed in this study.

3.2 Methodology

This study consisted of designing concrete mixes of different grades of 25 MPa, 35 MPa and 50 MPa, with each grade having cement substituted at four levels of 30%, 40%, 50% and 60%. The 30% mixes were used as reference mixes as the study is concerned with finding an optimum FA concrete mix that can be comparable or perform better than the standard 30% FA concrete. Concrete samples for testing were prepared in laboratory conditions. The mixing for test specimens took place at the laboratories at the DUT and Contest in accordance with ASTM C 685/C 685M-01 (2001) and SANS 5861-1:2006 (2006). The specimens for the compressive strength were made in the DUT laboratory with the concrete mixed by hand. The samples for the unit weight, air content, shrinkage and durability testing were made at the Contest laboratory and the concrete was mixed using an electric pan mixer as shown in Figure 3.1.

Fresh concrete specimens were tested for workability, time of setting, air content and density and the hardened concrete specimens were made as per SANS 5860:2006 (2006) for testing the compressive strength, durability index and shrinkage. The specimens for the hardened concrete tests were cast in moulds, removed in the following day and cured in water for the duration of up to one year. The specimens for the compressive strength tests were all stored in the same water tub, with the temperature regulated between 22°C and 25°C with a thermostat, from day one up to one year. The specimens were removed from the curing tub on the relevant testing days, at 1, 7, 14, 28, 56, 84, 180 and 365 days. These specimens were prepared and tested in accordance with SANS 5863:1994 (1994).

Figure 3.1: Mixing of concrete with an electric pan mixer.

3.3 Materials

3.3.1 Cement

Cements used in South Africa have to conform to certain physical and chemical requirements in accordance with SANS 50197-1 (2000). OPC 52,5N from PPC was used in this project as it does not contain any SCM. The SANS 50197-1 (2000) standard permits many different combinations of compositions in cements. In practice, however, the manufacturers are constrained by what is technically and economically feasible. Most of the suppliers in KwaZulu-Natal manufacture blended cements, using either slag or FA, and in other circumstances, South African Bureau of Standards (SABS) has approved the blending of cement with both slag and FA making up to 50% of the cement substitute. Unblended OPC CEMI 52,5N was used for this project to provide for more accurate cement replacement quantities. Tables 3.1 and 3.2 show the typical properties of OPC 52,5N.

Table 3.1: Chemical properties of OPC 52,5N (PPC Cement, 2011).

Chemical Properties	Typical OPC Results for PPC Group	SANS 50197-1 Requirements
Insoluble residue %	2,0	5,0 maximum
Sulphur Trioxide %	2,0	4,0 maximum
Loss of Ignition %	2,5	5,0 maximum
Chlorides %	< 0,01	0,1 maximum

Table 3.2: Physical properties of OPC 52,5N (PPC Cement, 2011).

Physical Properties	Typical SureBuild 52,5N Results for PPC Group	SANS 50197-1 Requirements
Setting times:		
Initial: minutes	125	45 minimum
Final: hours	2,5	No requirement
Specific Area (Blaine): m²/kg	400	No requirement
Compressive Strength (EN 196-1)		
At 2 days (MPa)	28	≥ 20,0
At 28 days (MPa)	±58	≥ 52,5 no maximum
Soundness: Le Chatelier Expansion (mm)	1	10 maximum
Densities:		
Relative density	3,14	
Bulk density, aerated, kg/m³	1100 – 1300	
Bulk density, as packed, kg/m³	1500	
Approximate Volume: 50kg bag, ℓ	±33	

3.3.2 Fly Ash

In South Africa, one can obtain both classified and unclassified FA. SANS 50450-1 (2014) classifies FA as having typical fineness on a 45 micron sieve of < 12%. Unclassified FA obtained from Lafarge Ash Resources at Matla Power station was utilized in this project. This FA is commonly used extensively in the construction industry although it does not conform to the requirements of SANS 50450-1 (2014) in terms of fineness. The results from the oxide analysis of the FA are shown in Table 3.3. The total sum of SiO_2, Al_2O_3 and FeO_3 is 85,91 and the total oxide is 99,07. This classifies the FA as Class F.

Table 3.3: Chemical composition of the FA from Matla Plant, (Appendix C).

Chemical	Composition (%)
Silica (SiO_2)	53,19
Aluminium Oxide (Al_2O_3)	30,12
Ferric Oxide (Fe_2O_3)	2,6
Manganese Oxide (Mn_2O_3)	0,03
Calcium Oxide (CaO)	5,74
Magnesia (MgO)	1,93
Phosphorus Oxide (P_2O_5)	0,16
Potassium Oxide (K_2O)	0,84
Sodium Oxide (Na_2O)	0,57
Titanium Dioxide (TiO_2)	1,65
Sulphur Trioxide (SO_3)	0,73
Strontium Oxide (SrO)	0,25
Chronium Oxide ($Cr_2O_{3)}$	0,00
Loss On Ignition (LOI) @ 950°C	1,25

3.3.3 Fine aggregates

River sand purchased from local suppliers was used in the laboratory tests. A sieve analysis of three samples of the fine aggregates was performed in accordance with ASTM C 136-06 (2006) and resulted in a Fineness Modulus (FM) of 2,13. The grading envelope from the sieve analysis results of the fine aggregates is shown in Appendix A.

3.3.4 Coarse aggregates

Size 9,5 mm tillite stone was obtained from the Lafarge Cato Manor Quarry. A sieve analysis test for three samples of the aggregates was performed in accordance with SANS 201:2008 (2008) and the grading envelope from the results is shown in Appendix B.

3.3.5 Water

The mixing water quality generally does not affect the quality of concrete or its properties, although it is commonly accepted that the water used in concrete should be clean and drinkable. Cold tap water was utilized in the concrete mixes.

3.3.6 Admixtures

This study concentrated on the effects on concrete due to the addition of FA, to obtain results that are not tainted by other materials. No admixes were used in the concrete mixes because they can have an effect on the amount of water that is used which could affect properties such as compressive strength.

3.3.7 Design mixing proportions

The mixing proportions for the mixes were designed according to ASTM C 685/C 685M-01 (2001) specifications. Firstly, three concrete mixes of grades 25 MPa, 35 MPa and 50 MPa, all with 30% FA were designed and produced for trial purposes. This was done to ensure that the designed 28-days compressive strengths were achieved before the actual testing commenced. These mixes were made and tested at the DUT laboratory. Table 3.4 shows the mix design for the trial mixes.

Table 3.4: Mix design for the trial mixes

Materials	25 MPa/30%FA	35 MPa/30%FA	50 MPa/30%FA
W/CM	0,61	0,47	0,37
Water (kg)	187,2	187,2	180
Total binder (kg)	306,89	398,30	486,49
Cement (kg)	214,82	278,81	340,54
FA (kg)	92,07	119,49	145,95
Stone (kg)	850	850	850
Sand (kg)	935,91	844,5	763,51

An example of materials proportions are shown in Figure 3.2 and the mix design for the test mixes is shown in Table 3.5.

Figure 3.2: Example of mix proportions used

Table 3.5: Mix design for test specimens

Concrete Mix (MPa/FA%)	W/C	Water (litres/m^3)	Total Binder (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	Stone (kg/m^3)	Sand (kg/m^3)
25/30	0,6	210	350	245	105	850	870
25/40	0,6	210	350	210	140	850	870
25/50	0,6	210	350	175	175	850	870
25/60	0,6	210	350	140	210	850	870
35/30	0,5	210	420	294	126	850	800
35/40	0,5	210	420	252	168	850	800
35/50	0,5	210	420	210	210	850	800
35/60	0,5	210	420	168	252	850	800
50/30	0,37	200	540,54	378,38	162,16	850	689,46
50/40	0,37	200	540,54	324,32	216,22	850	689,46
50/50	0,37	200	540,54	270,27	270,27	850	689,46
50/60	0,37	200	540,54	216,22	324,32	850	689,46

3.4 Laboratory testing

A number of laboratory tests were performed on the concrete specimens to determine the optimum amount of FA that could be used and still achieve desirable concrete mix. The specimens were made and prepared in accordance with ASTM C 192/C 192M-06 (2006) and SANS 5861-3:2006 (2006) specifications.

A total number of 252 cube specimens were made at the DUT laboratory and used for testing the compression strength of concrete samples. A total number of 24 cube specimens and five rectangular specimens were made at the Contest Laboratories for testing of fresh concrete properties. Table 3.6 shows the tests performed at the DUT and at the Contest Laboratories.

Table 3.6: Tests performed in the study

Test Description	Standard Specification	Laboratory
Sand Sieve Analysis	ASTM C136-06/ SANS 201	DUT
Stone Sieve Analysis	ASTM C136-06/ SANS 201	DUT
Workability - Slump	ASTM C143-90/ SANS 5862-1	DUT/ CONTEST
Compressive Strength	SANS 5863	DUT
Oxygen Permeability Index	SANS 3001-C03-2	CONTEST
Ion Chloride Conductivity	SANS 3001-C03-3	CONTEST
Sorptivity	SANS 3001-C03-4	CONTEST
Concrete Density	ASTM C138/ SANS 6250	CONTEST
Air Content	ASTM C138/ SANS 6252	CONTEST
Time of set	ASTM C403/ SANS 50196-3	CONTEST
Shrinkage	ASTM C157/ SANS 6085	CONTEST

3.4.1 Testing for concrete workability

The workability of concrete can be measured using many different methods such as Vebe test, Compaction factor test, Ball-penetration test and Slump test. The slump test was performed to determine the workability of the concrete mixes in this study. It determines the consistency of freshly mixed concrete in accordance with ASTM C 143/C 143M-15a (2015) and SANS 5862-1:2006 (2006) specifications. The slump test is illustrated in Figure 3.3.

The procedure for slump test is as follows:

1. Dampen the slump test mold and place it on a flat, moist, nonabsorbent, rigid surface, like a steel plate.
2. Fill the mold to ⅓ full by volume and rod the bottom layer with 25 evenly spaced strokes.
3. Fill the mold to ⅔ full and rod the second layer with 25 strokes penetrating the top of the bottom layer.
4. Heap the concrete on top of the mold, and rod the top layer with 25 strokes penetrating the top of the second layer.
5. Strike off the top surface of the concrete even to the top of the mold.
6. Remove the mold carefully in the vertical direction (taking about five seconds).
7. Immediately invert and place the mold beside the slumped concrete and place the rod horizontally across the mold, and measure the slump, in mm, to the nearest 5 mm.

The slump test should take approximately 2,5 min.

Figure 3.3: Slump test performed at the DUT laboratory.

3.4.2 Testing for concrete density and air content

The total volume of air in concrete is usually measured on the plastic concrete (Portland Cement Association, 1998: 2). The air content can be measured in different ways; the pressure method, the volumetric, gravimetric method and the free-air method. In this study we employed the gravimetric method in accordance with ASTM C 138/C 138M-16 (2016). The method involves filling up a steel cylinder with a concrete sample. The concrete is filled in three equal layers with each layer consolidated by rodding 25 times using a steel rod and tapping the sides of the cylinder 10 to 15 times. When the cylinder is filled up, the top is then struck off and the surface is made smooth and free of voids. The cylinder is cleaned and weighed to calculate the unit weight, yield, relative yield and air content.

The following formula was used to determine the air content percentage:

$$Air\ content\ = \left(\frac{Wmax - Wunit}{Wmax}\right) x\ 100 \qquad (3.1)$$

Where:

W_{max} = maximum theoretical weight

W_{unit} = actual unit weight

General recommendations on total air content for concrete are shown in Table 3.7.

Table 3.7: Recommended Total Target Air Content for Concrete (Portland Cement Association, 1998: 2)

Nominal maximum aggregate size (mm)	Air Content (%)		
	Severe exposure	Moderate exposure	Mild exposure
9,5	7,5	6	4,5
12,5	7	5,5	4
19,0	6	5	3,5
25,0	6	4,5	3

The project specifications usually allow the air content of the concrete to be within -1 to +2 percentage points of the table target values.

3.4.3 Testing for setting time of fresh concrete

One of the most useful definitions of setting is in the context of finishing concrete surface work. The “initial set” can be regarded as the time a concrete-finisher can stand on the concrete and leave a boot-print only about 25 mm deep. This is about the time that you can begin the first machine-float pass. As the concrete continues to stiffen, the concrete-finisher can observe that the boots only leave the slightest scuff on the concrete, indicating “final setting.”

There are many variations of testing for time of set and they provide varying results. The test that was used in this study was to insert probes into the mortar to a depth of about 25 mm as per ASTM C 403/C 403M-08 (2008). This test is referred to as “Standard Test Method for Time of Setting of Concrete Mixes by Penetration Resistance.” Although the words “concrete mixes” are used, this test is to measure the setting time of mortar. The test is performed by first sieving-out the coarse aggregate from a sample of fresh concrete, leaving a mortar that is tested for setting time. The time measurement starts and is recorded from the time the cement is mixed with water in the mix. At certain intervals, the probes are inserted to measure the depth at the pressure required to penetrate about 25 mm into the sample. The resulting value is then a mortar set time, which can be different from the concrete set time by a number of hours.

3.4.4 Testing for concrete compressive strength

The compressive strength test is regarded as the most significant performance measure for strength concrete. It measures the strength of concrete in Mega-Pascals (MPa) after a 28-days period of concrete curing. The test is usually performed by crushing cube specimens under a controlled-displacement hydraulic press machine as shown in Figure 3.4 and 3.5, in accordance with SANS 5863 (1994) after a specified period. Three cube specimens (made from the same concrete mix) are crushed and the results are averaged to give the compressive strength of the concrete for the specified period.

In this study, 24 cube specimens for each concrete mix were made and cast into 100 mm cube moulds as per SANS 5861-3:2006 (2006) and ASTM C 192/C 192M-06 (2006) specifications. The cubes were removed from the moulds after approximately 24 hours, referenced and then placed in a water tank for curing until they were tested. The water temperature in the tank was regulated between 22°C and 25°C with a thermostat. The testing for compressive strength commenced after one day to one year after casting the specimens. The specimens were tested at 1, 7, 14, 28, 56, 84, 180 days and one-year periods.

Figure 3.4: Controlled-displacement hydraulic press machine.

Figure 3.5: Crushing of a test cube specimen at the DUT laboratory.

3.4.5 Testing for concrete shrinkage

The linear shrinkage of concrete is measured in accordance with ASTM C157-08 (2008) and SANS 6085: 2006 (2006) specifications, by measuring the length change of a specimen over a certain period, at different intervals. In this study, the test was conducted by measuring the shrinkage of five 35 MPa concrete mixes with FA content of 0%, 30%, 40%, 50% and 60% over a period of 35 days.

Three specimens were made for each mix and they were cast into 100 mm × 100 mm × 300 mm cast iron moulds with measuring studs fixed at the two ends. The specimens were then removed from the moulds after 24 hours and the length of the specimens was measured on the comparator. After measurement, they were stored in lime-saturated water with the temperature regulated between 22°C to 25°C. At 7-days after casting, they were removed from the lime-saturated water and the initial comparator reading was taken for calculation of linear shrinkage. The specimens were then kept in a humidity-controlled drying room until the final comparator reading at 35-days. The change in length (ΔL) of each specimen was calculated from the difference of initial and the final comparator readings as follows;

$$\Delta Lx = \left[\frac{(CRD - CRDinitial)}{G}\right] x\ 100 \qquad (3.2)$$

Where:

ΔL_x = length change of specimen at any age, %,

CRD = difference between the comparator reading of the specimen and the reference bar at any age, and

G = the gauge length (300 mm)

The shrinkage strain (ΔL/L) was calculated after 35 days. Table 3.8 shows typical drying shrinkages of cement mortar and concrete.

Table 3.8: Typical drying shrinkages (Grieve, 1994: 32).

Material	Shrinkage (Microstrain)
Hardened cement paste	2 500 – 3 000
Mortar	600 – 1 200
Concrete	200 - 800

According to ASTM C 157-08 (2008), for specimens stored in water, the standard deviation (1s) among specimens is 0,0045%. When three replicate specimens are tested, the maximum range among them is not expected to exceed 0,0266% in 95% of the sets tested. When a test result represents the mean of three specimens, the 1s is 0,0026%. The difference between two such means is not expected to exceed 0,0074% in 95% of such duplicate tests performed.

For specimens stored in air, the standard deviation (1s) among specimens is 0,0084%. When three replicate specimens are tested, the maximum range among them is not expected to exceed 0,0496% in 95% of the sets tested. When a test result represents the mean of three specimens, the 1s is 0,0048%. The difference between two such means is not expected to exceed 0,0137% in 95% of such duplicate tests performed.

3.4.6 Testing for concrete durability

Durability can be better quantified by considering permeability and shrinkage of concrete, which are two performance characteristics that can prolong the service life of a structure that is subjected to severe exposure conditions. The durability of reinforced concrete structures depends on the quality and thickness of the cover layer and its ability to protect the reinforcing steel. Improved durability will not be assured unless some relevant durability parameters reflecting the quality of the cover layer can be measured – called 'Durability Indexes'. Such parameters should be linked with transport mechanisms that contribute to deterioration (Alexander, 2006: 5). Test methods have been developed to characterise the transport properties of concrete.

In the last decade researchers in South Africa have developed durability index tests that are unique to the country. These tests are Oxygen Permeability Index, Chloride Conductivity Index and Water Sorptivity Index tests. The durability indices obtained with these test methods have been related empirically to service life prediction models (Beushausen. and Alexander, 2008: 25). The South African durability index approach is currently being applied in a number of large scale construction projects in the country (Ballim, 2009: 77). The results of the tests are expressed as index values (Afrisam, n.d.: 121). The tests provide a relative indication of the resistance of the concrete to the ingress of chlorides and/or carbon dioxide.

Normally engineers specify the measurement of durability for structures in critical or in severely corrosive environments such as the marine splash zone. Limits for durability index values were suggested by Alexander et al, n.d., to classify concrete in terms of durability, to minimize corrosion of reinforcing steel. The minimum values were based on controlled laboratory studies and site data (Afrisam, n.d.: 124). The suggested ranges for durability classification of concrete, for three index tests currently used in South Africa are shown in Table 3.9.

Table 3.9: Acceptance criteria for durability index testing (Alexander, Mackechnie and Ballim, 1999: 25).

Durability Class	OPI (Log scale)	Sorptivity (mm/√h)	Cl Conductivity (mS/cm)
Excellent	>10	<6	<0,75
Good	9,5 - 10	6 - 10	0,75 – 1,50
Poor	9,0 – 9,5	10 - 15	1,5 – 2,50
Very Poor	< 9,0	>15	>2,50

The three durability index tests in this study were performed at the Contest laboratory, with the specimens prepared in accordance with ASTM C 192/C 192M-06 (2006) and SANS 3001-CO3-1:2015 (2015) specifications. The procedures for performing the tests are as follows:

a. *Oxygen Permeability Index (OPI) test*

The South African OPI test method is performed in accordance with SANS 3001-CO3-2:2015 (2015). It comprises measuring the pressure decay of oxygen passed through a concrete disk (typically 70 mm diameter by 25 mm thick) placed in a falling head permeameter. A pressure gradient is applied across the test specimen and subsequently the pressure decay in the pressure cell is monitored over time (The Concrete Portal, n.d.). The test is suitable for the evaluation of materials and mix proportions for design purposes, and for research and development. The test can also be used for quality control of concrete on site.

Four test specimens are required per test. Each specimen consists of a 70 mm ± 2 mm diameter concrete disc with a thickness of 25 mm ± 2 mm cored and cut in accordance with SANS 3001-CO3-2:2015 (2015) specifications. After a specified curing age requirement of the concrete specimen, the four specimens are prepared and placed in an oven for seven days. After seven days ± 4 hours the specimens are placed in desiccators for cooling. The temperature is kept to about 23ºC ± 2ºC for a cooling period of no less than two hours and no longer than four hours. Within thirty minutes of removing the specimens from the desiccators; they are put into the pressure vessel at a starting pressure of 100 kPa ± 5 kPa and may be terminated when the pressure has dropped to 50 kPa ± 2.5 kPa or after six hours ± 15 min, whichever occurs first. Readings are taken at intervals of 5 kPa ± 1 kPa pressure drop and time recorded. A minimum of eight readings is required and can be recorded automatically on the computer. See Figures 3.6 and 3.7.

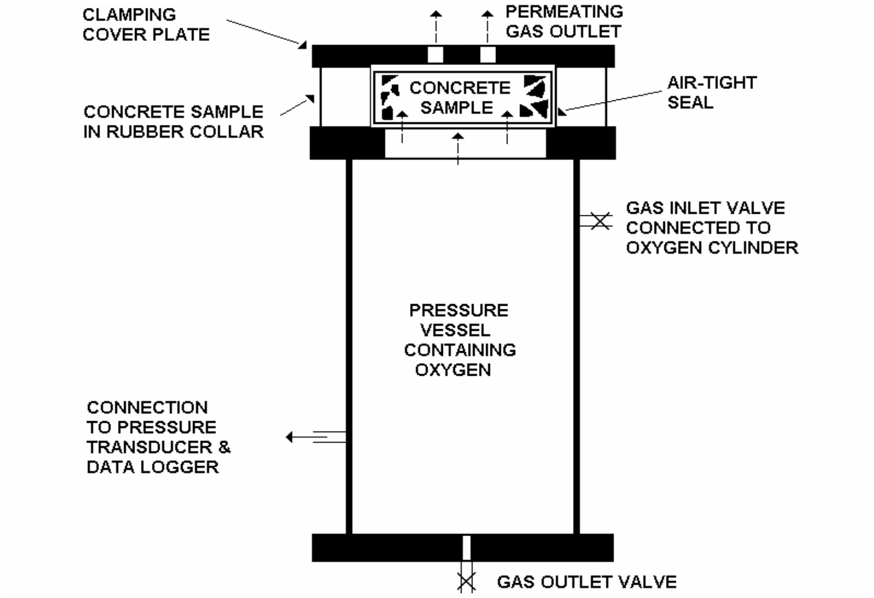


Figure 3.6: A schematic example of an OPI test apparatus (Durability Index Testing Procedure Manual, 2007: 5).

Figure 3.7: Arrangement of OPI test cylinders at Contest laboratory.

The coefficient of permeability is calculated for each of the test specimens. The OPI is given as the negative log of the average of the coefficients of permeability of the specimens, which for four specimens is:

$$OPI = -\,log_{10}[[¼\,(k1 + k2 + k3 + k4)] \quad (3.3)$$

Where:

k = coefficient of permeability of test specimen (m/s) from the Darcy's coefficient of permeability which is given by:

$$k = \frac{\omega Vgdz}{RA\phi} \quad (3.4)$$

OPI's are logarithmic values and range generally from 8 to 11, that is three orders of magnitude; the higher the index, the less permeable the concrete.

b. Water Sorptivity test

Sorptivity can be defined as the rate of movement of a wetting front through a porous material. The Water Sorptivity test involves the uni-directional absorption of water into one face of a pre-conditioned concrete disc sample (The Concrete Portal, n.d.). After conditioning concrete slices from cores or cylinders in a specified low humidity environment, the rate of absorption of water into one face of the disc is measured. Generally, sorptivity will decrease with lower W/CM and with increased maturity of the concrete.

The four test specimens used for the OPI are used for the Water Sorptivity test. Each specimen consists of a 70 mm ± 2 mm diameter concrete disc with a thickness of 25 mm ± 2 mm cored and cut in accordance with SANS 3001-CO3-4:2015 (2015). The marked specimen should be dry and the vertical circular surface should be sealed either with paint or masking tape. Their thickness and diameters are measured and recorded as well as the initial dry mass and then placed in a tray with 10 layers of paper towel and filled with $Ca(HO)_2$ solution.

The specimens are weighed at predetermined intervals and put back into the tray with the $Ca(HO)_2$ solution. Within a maximum of one day after weighing of the specimen is completed, the specimens are placed in a vacuum saturation tank. They are kept in the tank under pressure of -75 kPa to -80 kPa for three hours ± 15 min and then the tank is filled with $Ca(HO)_2$ saturated water, with air prevented from entering the vacuum chamber. After one hour ± 15 min, the vacuum is released and air is allowed to enter. The specimens are soaked for a further 18 hours ± one hour.

After 18 hours ± one hour soaking, the specimens are removed from the solution, the surface is dried to a saturated surface dry (SSD) condition with a paper towel, and immediately weighed to an accuracy of 0,01 g. The vacuum saturated mass M_{sv} of the specimen is weighed and recorded and the sorptivity is determined from the plot of mass of water absorbed versus square root of time.

The effective porosity (n) of each specimen is determined as follows:

$$n = \left[\frac{Msv - Ms0}{GAD\rho w}\right] x \; 100 \qquad (3.5)$$

Where:

n = effective porosity

M_{sv} = the vacuum saturated mass.

M_{s0} = mass of the specimen at t = 0 to the nearest 0,01 g.

A = cross-sectional area of the specimen to the nearest 0,02 mm^2.

D = average specimen thickness to the nearest 0,02 mm.

ρ_w = density of water = 10^{-3} g/mm^3.

The water sorptivity of the specimen (S) is given by;

$$s = \frac{Fd}{Msv - Ms0} \qquad (3.6)$$

Where:

F = the slope of the best fit line (5 g), in grams per square root of the hour. Other parameters are as previously described.

The lower the water sorptivity index, the better is the potential durability of the concrete. Sorptivity values typically vary from approximately 5 mm/√h, for well-cured concrete, to 20 mm/√h for poorly cured concrete. The typical test arrangement is shown in Figure 3.8 (Holcim SA, 2006: 163).

Figure 3.8: Typical Water Sorptivity test apparatus (Holcim South Africa, 2006: 163)

c. Chloride Conductivity (CC) test

The Chloride Conductivity test involves the measurement of a sample's electric conductivity in accordance with SANS 3001-CO3-3:2015 (2015) method. Four test specimens are required per test. The test specimen shall consist of a 70 mm ± 2 mm diameter concrete disc with a thickness of 25 mm ± 2 mm cored and cut in accordance with Durability Index Testing Procedure Manual, 2007. The concrete specimens are dried in an oven and vacuum pre-saturated with a 5 M NaCl solution.

The specimens are placed in the vacuum saturation tank that is evacuated to between -75 and -80 kPa and is maintained under vacuum of between -75 and -80 kPa for 3 hours ±15 min. After three hours ±15 min the tank is isolated and the salt solution is allowed to enter the vacuum tank without releasing the vacuum to cover all the specimens to a depth of approximately 40 mm. The vacuum is re-established between -75 kPa and -80kPa and maintained for one hour ± 15 minutes. After one hour ± 15 min, the vacuum is released and air is allowed to enter. The specimens are then soaked for a further 18 hours ± one hour. After 18 hours ± one hour soaking, the specimens are removed from the solution and the surface is dried with a paper towel to a SSD condition and weighed. This is recorded as the vacuum saturated mass M_S of the specimen. The test procedure commences immediately after this weighing.

A conduction cell is used, in which the sample is placed between two cells containing 5 M NaCl solution as shown in Figures 3.9 and 3.10. A potential difference is applied across the sample, causing a movement of chloride ions, and the corresponding current is used to calculate the concrete's conductivity, which in turn can be related to the concrete's resistance to chloride ingress. This procedure gives an instant reading.

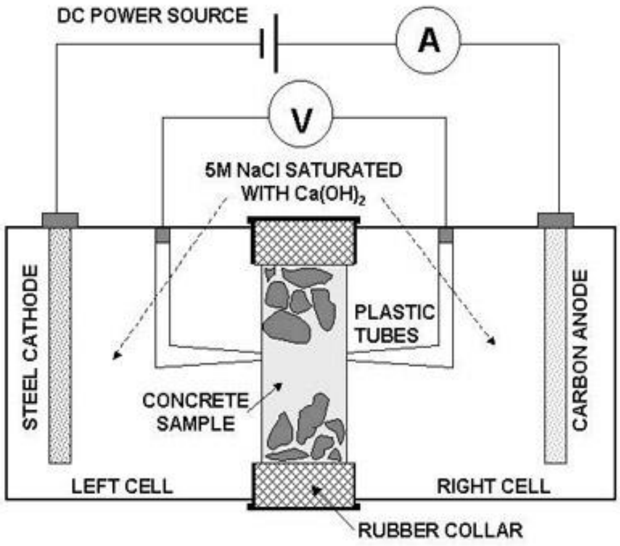


Figure 3.9: Schematic drawing of Chloride Conductivity test apparatus (The Concrete Portal, n.d.)

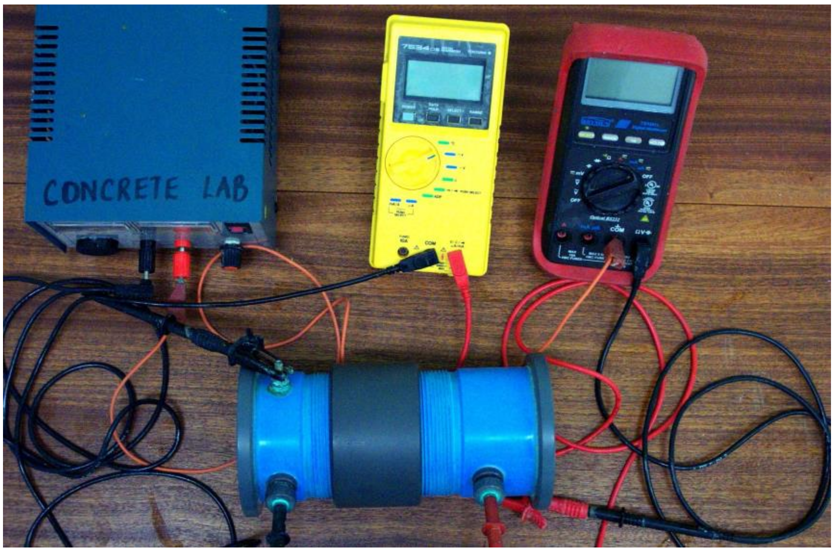


Figure 3.10: Typical Chloride Conductivity test apparatus (Alexander, 2006: 7)

For each test specimen, the Chloride Conductivity is calculated individually using the equation;

$$\sigma = \frac{it}{VA} \tag{3.7}$$

Where:

σ	= conductivity of the specimen (mS/cm).
i	= electric current (mA.)
V	= voltage difference (V).
t	= average thickness of specimen (cm).
A	= cross-sectional area of the specimen (cm^2).

The porosity (n) of each specimen is determined as follows:

$$n = \left[\frac{Ms - Md}{\mathrm{AD\rho w}}\right] x\ 100 \qquad (3.8)$$

Where:

n	= effective porosity
Ms	= the vacuum saturated mass of the specimen the nearest 0,01 g
Md	= mass of the dry specimen to the nearest 0,01g.
D	= average specimen thickness to the nearest 0,02 mm.
ρw	= density of salt solution = 1,19 $x10^{-3}$ g/mm3.

Typical Chloride Conductivity index values range from > 3 mS/cm for M20 – M30 OPC concretes, to < 0,75 mS/cm for M40 – M50 slag or FA concretes. The lower the index, the better is the potential durability of the concrete. Table 3.10 shows maximum 28-days Chloride Conductivity values (mS/cm) for 50-year design life in SA marine conditions.

Table 3.10: Maximum 28-days Chloride Conductivity values for 50-year design life in SA marine conditions (The Concrete Portal, n.d.).

Exposure	Cover (mm)	10% CSF	100% PC	30% FA	50% Slag
Extreme	40	0,25	0,45	0,75	0,85
	60	0,3	0,95	1,35	1,55
	80	0,6	1,3	1,8	2
Very Severe	40	0,35	0,45	0,90	1,10
	60	0,50	1,15	1,75	2,00
	80	0,85	1,65	2,30	2,60
Severe	40	0,55	1,00	1,85	1,95
	60	1,10	1,85	2,95	3,05
	80	1,55	2,50	3,75	3,85

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 Introduction

Numerous tests were performed under laboratory condition over a period of one year to evaluate the effect of using high content FA in concrete mixes compared to the standard 30% FA concrete. Before the actual testing commenced, trial mixes were designed and made, to control the desired strengths of the different grades of concrete.

4.2 Trial mixes

Trial mixes of 25 MPa, 35 MPa and 50 MPa with 30% FA were produced at the DUT laboratory for control purposes. This was to ensure that the desired 28-days compressive strength was achieved. Table 4.1 shows the mix proportions used for the trial mixes.

Table 4.1: Trial mixes proportions.

Materials	25 MPa/30%FA	35 MPa/30%FA	50 MPa/30%FA
W/CM	0,61	0,47	0,37
Water (kg)	2	2	2,2
Cement (kg)	2,15	2,79	3,4
FA (kg)	0,92	1,19	1,46
Stone (kg)	8,5	8,5	8,5
Sand (kg)	9,36	8,45	7,64

The trial mixes were tested for compressive strength at 7, 14 and 28-days and the results are shown in Table 4.2. From the table it can be seen that both 35 MPa and 50 MPa mixes achieved the desired strength and the 25 MPa mix fell short of the design strength. Slight adjustments were made in the 25 MPa mix for testing purposes, by decreasing the W/CM from 0,61 to 0,6 to ensure the required 28-days strength was achieved. The trial mixes tests results are presented in Figures 4.1, 4.2, and 4.3.

Table 4.2: 28-days compressive strength results for the trial mixes.

Mix Description	Cast Date	Average Compressive Strength (MPa)		
		7 days	14 days	28 days
25/9,5-30%FA	10/05/2013	14	17,2	21,7
35/9,5-30%FA	10/05/2013	24,4	31,1	39,5
50/9,5-30%FA	10/05/2013	35,8	44,7	53

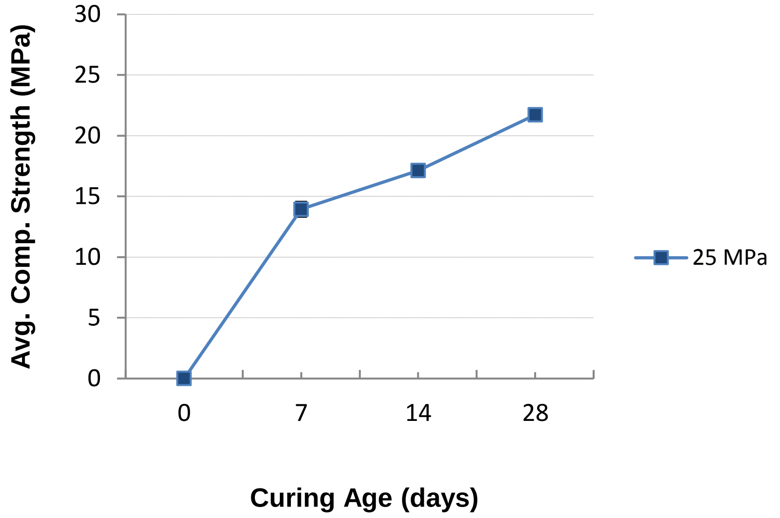


Figure 4.1: 28-days compressive strength results for Grade 25 MPa trial mix.

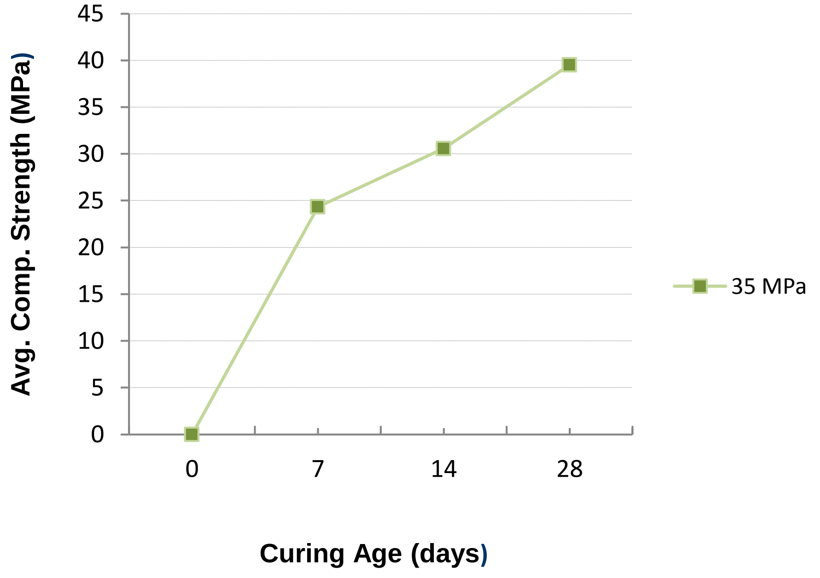


Figure 4.2: 28-days compressive strength results for Grade 35 MPa trial mix.

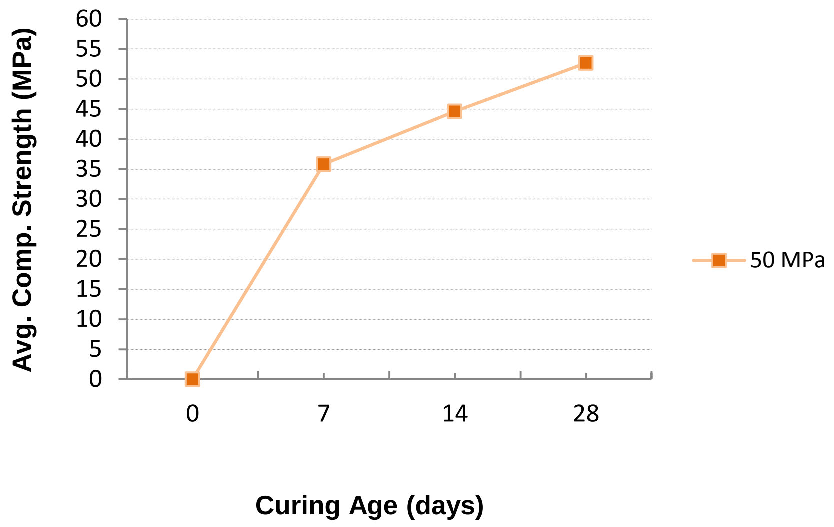


Figure 4.3: 28-days compressive strength results for Grade 50 MPa trial mix.

4.3 Evaluating fresh concrete properties

Four FA concrete mixes with W/C ratios of 0,5 and maximum design slump of 100 mm were produced at the Contest Laboratory, in accordance with ASTM C 685/C 685M-01 (2001) specifications, with the FA partially substituting cement at 30%, 40%, 50% and 50%. The mix proportions for the 35 MPa mixes produced at the Contest laboratory are shown in Table 4.3, and the plastic properties results for the mixes (extracted from Appendix E) are shown in Table 4.4. Only the 35 MPa concrete mixes were evaluated for testing of fresh concrete as the experiment was aiming at determining how the increase of FA quantity affected the plastic properties of a particular mix, and 35 MPa is commonly used in practice for structural concrete.

Table 4.3: Mix proportions for the Grade 35MPa concrete mixes.

Materials (kg)	35 MPa/0FA	35 MPa/30FA	35 MPa/40FA	35 MPa/50FA	35 MPa/60FA
Cement	7,6	5,32	4,56	3,8	3,04
FA	0,00	2,28	3,04	3,8	4,56
Stone	17	17	17	17	17
River sand	17,2	17,2	17,2	17,2	17,2
Water	4,5	4,5	4,5	4,5	4,5

Table 4.4: Plastic properties for the Grade 35 MPa concrete mixes.

Description	35 MPa/0FA Ref. CT1148	35 MPa/30FA Ref. CT1032	35 MPa/40FA Ref. CT1039	35 MPa/50FA Ref. CT1048	35 MPa/60FA Ref. CT1054
FA (%)	0	30	40	50	60
Slump (mm)	55	70	85	85	75
Air content (%)	0,5	2,1	2,2	2,0	1,3
Density (kg/m^3)	2295	2295	2296	2282	2295

From the results, it was observed that with the increase of the FA volume affected the plastic properties, especially the slump. Figure 4.4 represents the results recorded from the slumps tests. The increase in FA content resulted in concrete with slightly higher slump compared to the concrete containing no FA. The conventional mix with no FA attained the lowest slump of 55 mm, and the mixes with FA achieved slump raging between 70 mm and 85 mm. Although the slump increased with the increase in FA content, the slump for the 60% mix was lower than the 40% and 50% mixes. This could be attributed to inconsistency in time taken to mix the concrete. As discussed in the literature, the increase of slump in the FA mixes may be attributed to the spherical shape of the FA particles, which promotes cohesion in the concrete. Although the slump increased with the increase of FA volume, this does not necessarily translate to less water required for the designed slump, as the differences between the recorded slumps are considerably small.

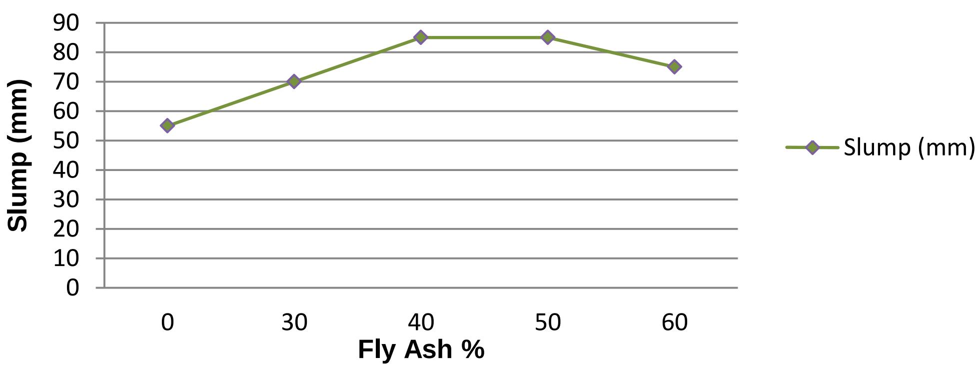


Figure 4.4: Slump test results for the Grade 35 MPa mixes.

Looking at the air content results, calculated using the gravimetric method, it was observed that the air content of the mixes was affected by the addition of FA, although the FA mixes did not seem to significantly vary or follow any particular trend. The ordinary concrete without FA has a very low air content of 0,5% while the FA mixes had air content ranging from 1,3% to 2,2%. The 40% FA mix has the highest air content, closets to the design amount of 3%. The increase of FA increased the air content of concrete, which can be beneficial for air- entrained concrete. The increase of FA did not have a significant effect in the density of concrete.

The results obtained from evaluating the plastic properties of the 35 MPa mixes show that the increase of FA can have a positive effect on fresh concrete, with the 40% mix getting the most favorable results, although the results do not vary considerably.

4.4 Evaluating the setting time of mortars

Measuring the setting time of concrete can yield different results almost every time, as the setting can be affected by a number of factors such as the room temperature, the type of testing method employed and the type of materials used. The determination for setting time for a 35 Mpa concrete mix with FA content at 0%, 30%, 40%, 50% and 60% was done at Contest laboratory. The recorded setting times of the mortar samples are shown in Table 4.5.

Table 4.5: Setting time for the Grade 35 MPa concrete mixes in a laboratory

Mix Description	Lab. Reference	Initial Setting (Hrs:min)	Final Setting (Hrs:min)
35/9,5-0%FA	CT1148	7	8:45
35/9,5-30%FA	CT1032	8:40	12:24
35/9,5-40%FA	CT1039	-	13:47
35/9,5-50%FA	CT1048	10:40	13:28
35/9,5-60%FA	CT1054	11:24	14:38

The setting time results show that by increasing the FA content, the concrete takes longer to set. The ordinary concrete took less time to set than the FA mixes, starting at seven hours. The concrete with the most FA volume took the longest time to set after 11 hours and 24 min. The setting of ordinary concrete took 105 min while the FA concrete mixes took between 168 min and 224 min to set. This is consistent with the literature as the hydration process is slower when the cement content is decreased, thus making the concrete set slower than ordinary concrete. It is observed that a 10% increase of FA content extends the initial setting time by average of 1,5 hours. There is no trend observed with regard to the total time taken to set for FA mixes as the 50% FA mix took 168 min to set while the 30% FA mix took the longest time at 224 min. These results prove that the addition of FA prolongs the setting time of concrete, as the hydration process is slower due to reduced generated heat.

4.5 Evaluating the drying shrinkage of concrete

The testing for the drying shrinkage of concrete was conducted at the Contest Laboratory in accordance with SANS 6085:2006 (2006) specifications. The 35 Mpa concrete mixes produced were measured over 35 days. The reporting on the results is shown in Table 4.6, extracted from Appendix F. From the results, we can note that the increase of FA content has an effect on the concrete, in terms of shrinkage. The concrete with the lowest FA volume has the lowest average shrinkage of 0,045% and the mix with the highest FA volume has the highest shrinkage of 0,056%.

Table 4.6: Drying shrinkage results for the Grade 35 MPa concrete mixes.

Mix Description	Laboratory Reference	Initial Shrinkage (%)			Avg. Shrinkage (%)
		Sample 1	Sample 2	Sample 3	
35/30%FA	CT1032	0,046	0,046	0,044	0,045
35/40%FA	CT1039	0,051	0,048	0,047	0,049
35/50%FA	CT1048	0,054	0,055	0,054	0,054
35/60%FA	CT1054	0,054	0,057	0,056	0,056

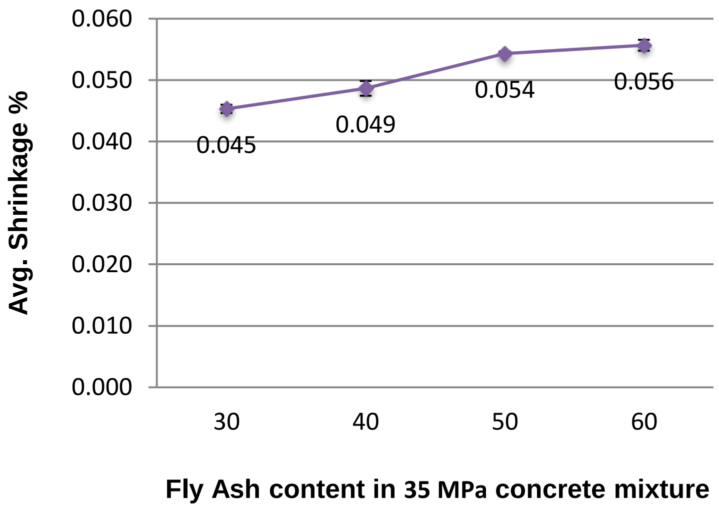


Figure 4.5: Drying shrinkage results for Grade 35 MPa mixes with different FA volume

Figure 4.5 shows the graphical representation of the drying shrinkage results. It is observed that the increase in the FA content has a potential of increasing the drying shrinkage of concrete. The shrinkage of concrete is expected to continue over the years and these results can significantly change over longer periods. Although this study has shown that the increase of FA volume increased the drying shrinkage, a number of studies on drying shrinkage seem to contradict each other on how the inclusion FA in concrete affects the concrete shrinkage. This may be due to a number of factors such as the type of materials used.

4.6 Testing for the compressive strength of concrete

The compressive strength testing was performed on 100 mm × 100 mm × 100 mm concrete specimens at the DUT laboratory. Twelve mixes of grades 25 MPa, 35 MPa and 50 MPa, with FA content of 30%, 40%, 50% and 60% were produced and 24 cube specimens were made for each mix, from the mix proportions shown in Table 4.7. The specimens were tested from one day to one year of age in accordance with SANS 5863 (1994) specifications. The compressive strength results of the specimens, extracted from Appendix D, are shown in Table 4.8.

Table 4.7: Mix proportions for the compressive strength tests mixes used.

Mix (MPa/%FA)	Cement (kg)	FA (kg)	Stone (kg)	Sand (kg)	Water (*l*)
25 MPa/9,5mm - 30%FA	7,85	3,364	23,27	27,58	6,84
35 MPa/9,5mm - 30%FA	10,19	4,366	23,27	24,21	6,84
50 MPa/9,5mm - 30%FA	12,94	5,546	23,27	20,24	6,84
25 MPa/9,5mm - 40%FA	6,73	4,485	23,27	27,58	6,84
35 MPa/9,5mm - 40%PFA	8,73	5,821	23,27	24,21	6,84
50 MPa/9,5mm - 40%FA	11,09	7,395	23,27	20,24	6,84
25 MPa/9,5mm - 50%FA	5,607	5,607	23,27	27,58	6,84
35 MPa/9,5mm - 50%FA	7,277	7,277	23,27	24,21	6,84
50 MPa/9,5mm - 50%FA	9,243	9,243	23,27	20,24	6,84
25 MPa/9,5mm - 60%FA	4,49	6,728	23,27	27,58	6,84
35 MPa/9,5mm - 60%FA	5,82	8,732	23,27	24,21	6,84
50 MPa/9,5mm - 60%FA	7,39	11,092	23,27	20,24	6,84

Table 4.8: Compressive strength tests results.

Mix Description	Cast Date	Average Compressive Strength (MPa)							
		1 day	7 days	14 days	28 days	56 days	84 days	6 months	1 year
25/9,5-30FA	11/09/2013	2,5	14,2	21,1	32	43	46,6	46,5	48
25/9,5-40FA	20/09/2013	2,2	14,2	18,5	26,8	35,5	38	39,6	41,2
25/9,5-50FA	03/10/2013	1,9	11,6	18,6	26,3	34,8	36,9	42,1	42,9
25/9,5-60FA	09/10/2013	1,4	8,1	12,7	23	29,2	27,6	29,7	32,4
35/9,5-30FA	12/09/2013	1,7	18,9	30	42,9	53,6	57,7	55,9	60
35/9,5-40FA	23/09/2013	1,8	17,3	27,2	40,9	52	55,8	55,2	58
35/9,5-50FA	04/10/2013	1,3	12,9	25,3	35,7	46,1	49	49,3	53,3
35/9,5-60FA	10/10/2013	4,6	13,9	20,8	34,5	43	43,4	47,5	51,8
50/9,5-30FA	18/09/2013	10,7	38,9	46,6	64,1	75,2	79	82,7	83,7
50/9,5-40FA	01/10/2013	3,7	24	38,2	48	59,7	65,2	65,7	67,3
50/9,5-50FA	07/10/2013	1,4	21,5	32,8	52,6	62,8	64,4	65,5	66
50/9,5-60FA	11/10/2013	6,4	25,1	36,9	53,2	60,2	60,6	63,2	66,3

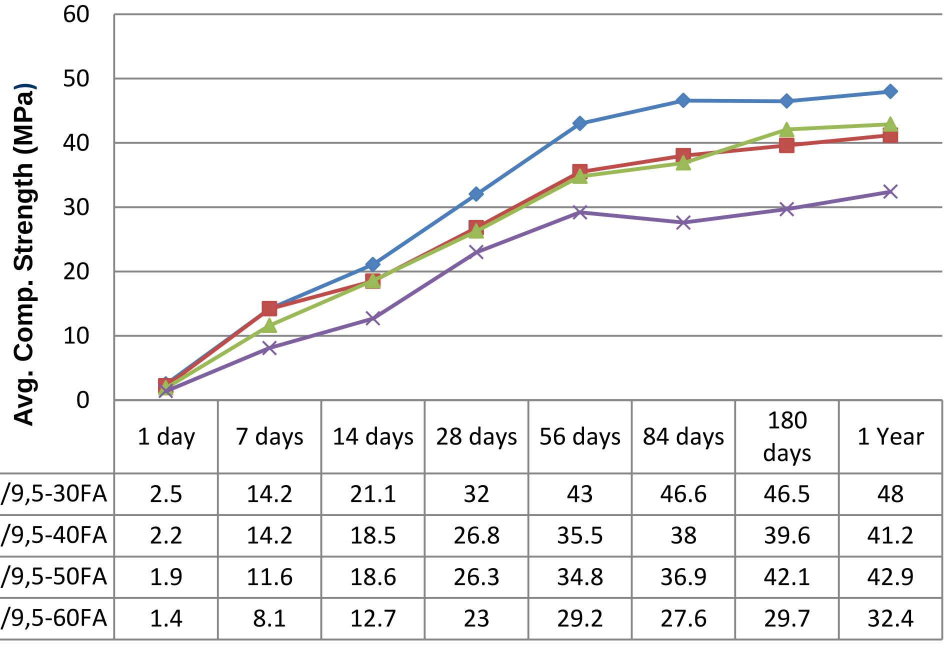
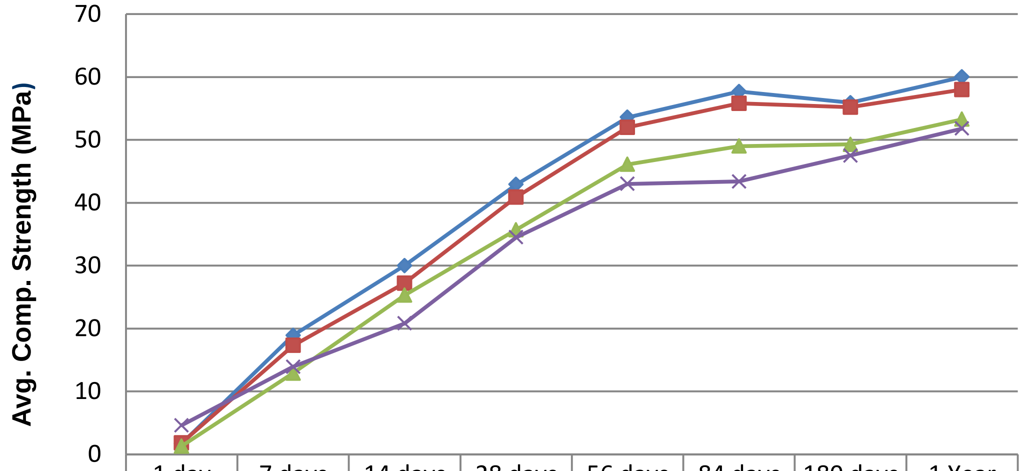
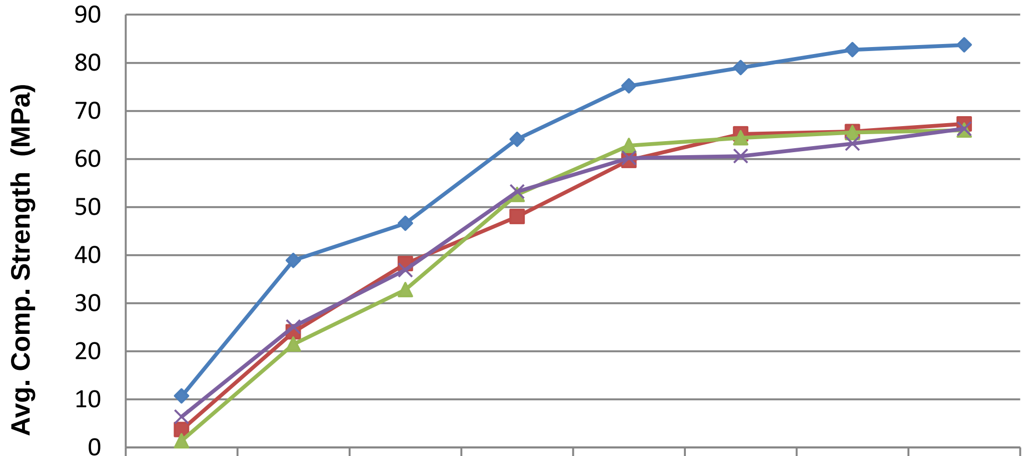


Figure 4.6: Compressive strength results for the Grade 25 MPa concrete mixes.



	1 day	7 days	14 days	28 days	56 days	84 days	180 days	1 Year
35/9,5-30FA	1.7	18.9	30	42.9	53.6	57.7	55.9	60
35/9,5-40FA	1.8	17.3	27.2	40.9	52	55.8	55.2	58
35/9,5-50FA	1.3	12.9	25.3	35.7	46.1	49	49.3	53.3
35/9,5-60FA	4.6	13.9	20.8	34.5	43	43.4	47.5	51.8

Figure 4.7: Compressive strength results for the Grade 35 MPa concrete mixes.



	1 day	7 days	14 days	28 days	56 days	84 days	180 days	1 Year
50/9,5-30FA	10.7	38.9	46.6	64.1	75.2	79	82.7	83.7
50/9,5-40FA	3.7	24	38.2	48	59.7	65.2	65.7	67.3
50/9,5-50FA	1.4	21.5	32.8	52.6	62.8	64.4	65.5	66
50/9,5-60FA	6.4	25.1	36.9	53.2	60.2	60.6	63.2	66.3

Figure 4.8: Compressive strength results for the Grade 50 MPa concrete mixes.

The compressive strength test results shown in Table 4.8 were represented in Figures 4.6, 4.7 and 4.8. The results show that the increase of FA content resulted in lesser compressive strength for all the mixes. In all the concrete grades, the mix control mix, 30% FA content, gained higher strength than the other FA mixes. For the grade 25 MPa mix, the 30%, 40% and 50% mixes gained required strength at 28-days and the strength continued to above 40 MPa after one year. Although the 60% mix gained slightly less strength than the required strength after 28-days, it is not of much concern as it can be seen that within 56 days it does gain the required strength. Looking at the grade 35 MPa and 50 MPa mixes, the trend continues where the 30% FA mix gained higher strength than the others did, and within the 28-days, all the mixes gained acceptable strength, which continues to grow at 56-days and throughout the one-year period. The 40% FA mix in grade 35 MPa attained very impressive results close to the 30% FA mix, where the average difference in both mixes is 2 MPa.

It is observed that the strength development of mixes with higher FA content is slow at early stages than the control 30% FA mix, but continues to grow steadily throughout the one-year period. This is consistent with the literature and previous studies, which have found that the less cement used in the mix results in slow early strength development due to lower heat evolution during hydration process, and the pozzolanic reaction boosts the strength at later stages.

The strengths gained by the 40% and the 50% FA mixes show that FA can partially substitute cement at these levels and perform reasonable well when compared to the 30% FA mixes. These mixes gained an average of ±15 MPa more than the required strength after a one-year period. If the concrete structure is exposed to continuous moisture to prolong curing time, as in the case of water retaining structures, it can be expected for the concrete to further gain more strength due to the pozzolanic reaction.

The results obtained in this study are comparable to other studies where the increase of FA volume in concrete mixes tends to decrease the compressive strength (Durán-Herrera et al., 2011), however the required design strength can still be achieved, as shown in all the results, especially the 40% and 50% FA mixes.

4.7 Evaluating the durability index

Three concrete durability index tests, Oxygen Permeability, Water Sorptivity and the Chloride Conductivity, were performed on the grade 35 MPa mixes at the Contest Laboratory after 7 and 28 days of water curing (see Appendixes G and H). These tests provide a relative indication of the resistance of the cover concrete to the ingress of chlorides and/or carbon dioxide.

4.7.1 Oxygen Permeability testing

The results obtained from the OPI testing are shown in Table 4.9. The testing was performed after 7 days and 28 days of age and the results are graphically represented in Figures 4.9 and 4.10.

Table 4.9: OPI tests results for the Grade 35 MPa concrete mixes.

Mix Grade	F.A %	Cast date	Age (days)	Sample A	Sample B	Sample C	Sample D	Avg. Log	CoV (%)
35/9,5-30FA	30	13/09/2013	7	9.92	9.6	9.5	9.85	9.72	2.1
35/9,5-40FA	40	13/09/2013	7	9.7	9.35	9.65	9.61	9.58	1.63
35/9,5-50FA	50	13/09/2013	7	9.46	9.34	9.42	9.35	9.39	0.61
35/9,5-60FA	60	13/09/2013	7	9.21	9.03	9.19	9.04	9.12	1.05
35/9,5-30FA	30	13/09/2013	28	9.95	10.32	10.08	10.08	10.11	1.53
35/9,5-40FA	40	13/09/2013	28	10.16	10.21	10.02	10.02	10.10	1
35/9,5-50FA	50	13/09/2013	28	10.01	10.07	9.82	9.79	9.92	1.4
35/9,5-60FA	60	13/09/2013	28	9.94	9.88	9.89	9.66	9.84	1.3

From Figure 4.9 is it observed that after 7 days of curing in water the 35 MPa/ 30% FA mix had the highest OPI value and the 35 MPa/ 60% FA mix has the lowest and poor results. This shows that at early stages, the lower the FA content, the lower is the permeability of concrete. Although at 7-days the mixes with FA content higher than 30% attained poor results, the 40% mix still has good acceptable results above 9,5. After 28 days, curing period the permeability results for all the mixes improves as it can be noted that the 40% mix results were very compatible with the control mix of 30% FA at 10,10 and 10,11 respectively. The high content FA mixes results increased more than the 30% mix after 7 days of curing. While the 30% mix results increased by 0,39, the 60% mix results increased by 0,72. Both the 30% and 40% mixes obtained excellent results above 10. The 50% and 60% mixes obtained good results above 9,5. These results are expected to continue improving with time after the pozzolanic activity that occurs after 28 days.

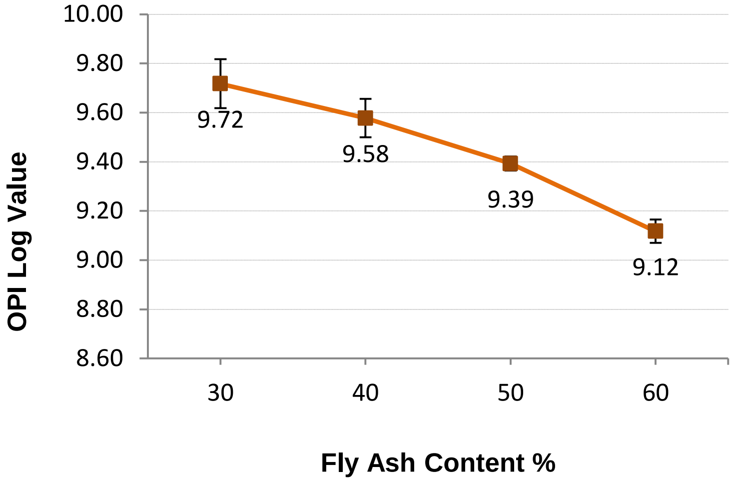


Figure 4.9: 7-days OPI tests analysis for the Grade 35 MPa concrete mixes.

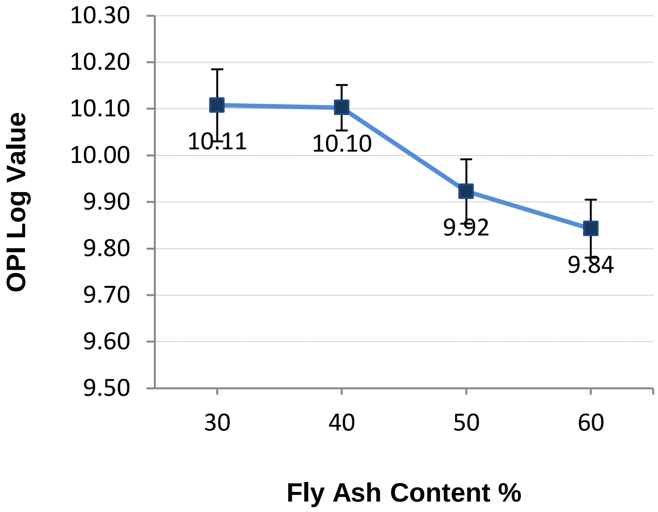


Figure 4.10: 28-days OPI tests analysis for the Grade 35 MPa concrete mixes.

4.7.2 Water Sorptivity testing

The Water Sorptivity test results for the 35 MPa/9,5mm mixes with different FA percentage after 7 and 28 days of water curing are shown in Table 4.10. Figures 4.11 and 4.12 represent the Water Sorptivity results for the 35 MPa FA mixes after 7 and 28 days of moist curing. The results illustrate that the 30% FA mix performed better than the higher FA content mixes, obtaining 11,5168 mm/√hr after 7 days and improving to 9,68 mm/√hr after 28 days. At early stages, the margin between the results is very big, but after 28 days, the other mixes improved considerable. The mix with the highest FA volume improved better than all other mixes after 28 days of curing, moving from 17,62 mm/√hr to 10,57 mm/√hr.

Table 4.10: Water Sorptivity tests results for the Grade 35 MPa concrete mixes.

Mix Grade	F.A %	Cast date	Age (days)	Sample A (mm/√hr)	Sample B (mm/√hr)	Sample C (mm/√hr)	Sample D (mm/√hr)	Avg. (mm/√hr)	CoV
35/9,5 MPa	30	13/09/2013	7	10,63	11,99	13,04	10,39	11,51	10,75
35/9,5 MPa	40	13/09/2013	7	13,33	13,45	13,65	14,21	13,66	2,84
35/9,5 MPa	50	13/09/2013	7	14,15	15,12	14,56	15,63	14,87	4,34
35/9,5 MPa	60	13/09/2013	7	18,84	17,37	20,6	13,67	17,62	16,71
35/9,5 MPa	30	13/09/2013	28	10,27	9,27	9,53	9,64	9,68	4,38
35/9,5 MPa	40	13/09/2013	28	8,5	9,26	10,18	13,25	10,30	10,3
35/9,5 MPa	50	13/09/2013	28	9,42	11,22	9,6	10,47	10,18	8,2
35/9,5 MPa	60	13/09/2013	28	9,39	11,09	10,83	10,95	10,57	7,46

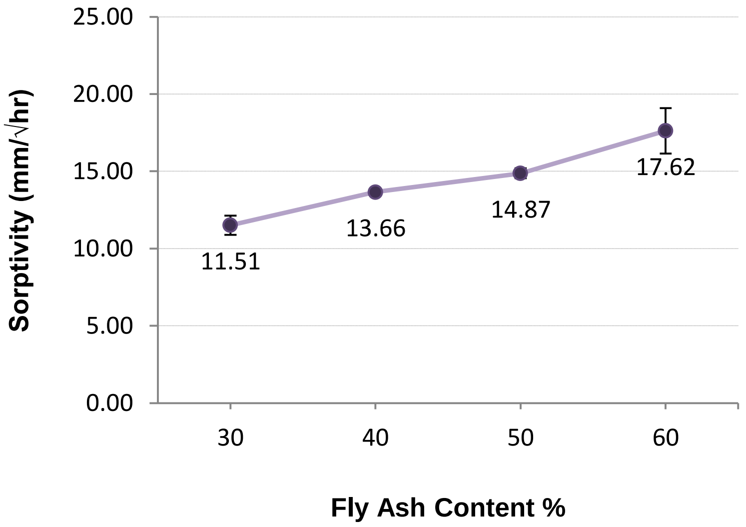


Figure 4.11: 7-days Water Sorptivity tests analysis for the Grade 35 MPa concrete mixes.

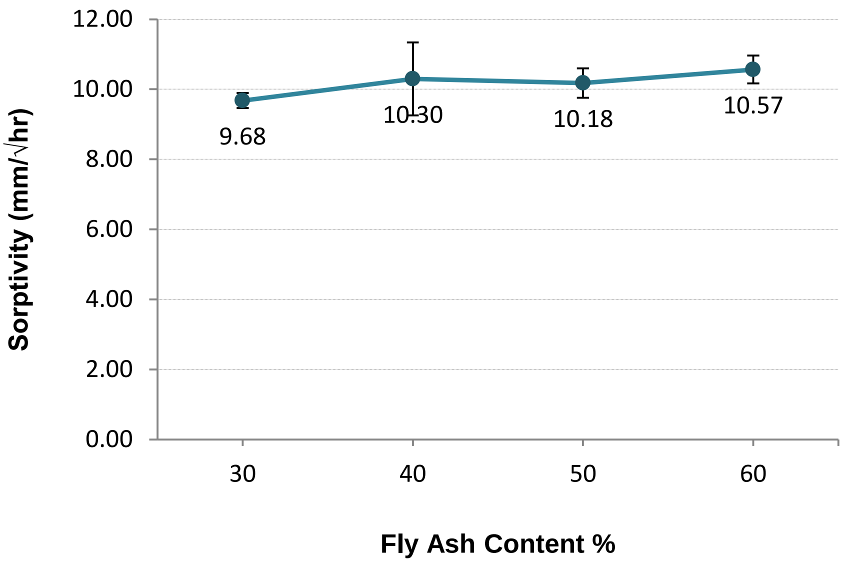


Figure 4.12: 28-days Water Sorptivity tests analysis for the Grade 35 MPa concrete mixes.

All the mixes had poor results after 7 days with the 60% mix having very poor results above 15 mm/√hr. With age, the results improved with the 30% mix having good results below 10 mm/√hr and the high volume FA mixes having poor results above 10 mm/√hr. It is not conclusive whether the inclusion of FA has a detrimental effect on concrete or not, when it comes to water sorptivity, as the results obtained can be accepted for as-built structures. It is clear that with time the FA mixes results improve considerable that is due to the pozzolanic activity that happens at later stages of concrete.

4.7.3 Chloride Conductivity testing

Table 4.11 shows the results obtained after testing the four 35 MPa mixes for Chloride Conductivity. Figure 4.13 and Figure 4.14 show a representation of the chloride penetration results for the mixes after 7 and 28 days of curing respectively. Figure 4.13 illustrates that at early days (7 days), the Chloride Conductivity results are. At 7-days, the 40% FA mix has the lowest index at 2,04 mS/cm while the 60% FA mix has the highest index 2,78 mS/cm. All the mixes show significant improvement after 28 days with the 50% mix performing better than the other mixes. The 50% and 60% mixes attained good results, below 1,5 mS/cm, which shows a similar trend with the study done by Burden (2006), where the concrete mixes with higher FA (40% and 50%) volume performed better than the 0% and 30% mixes after 90 days of curing.

Table 4.11: Chloride Conductivity tests results for the Grade 35 MPa concrete mixes.

Mix Grade	F.A %	Cast date	Age (days)	Sample A (mS/cm)	Sample B (mS/cm)	Sample C (mS/cm)	Sample D (mS/cm)	Avg. (mS/cm)	CoV
35/9,5 MPa	30	13/09/2013	7	2,2	2,14	2,26	2,23	2,21	2,4
35/9,5 MPa	40	13/09/2013	7	2,17	2	1,97	2	2,04	4,4
35/9,5 MPa	50	13/09/2013	7	2,07	2,25	2,03	2,1	2,11	4,5
35/9,5 MPa	60	13/09/2013	7	2,65	2,77	3	2,71	2,78	5,5
35/9,5 MPa	30	13/09/2013	28	1,59	1,53	1,65	1,66	1,61	3,8
35/9,5 MPa	40	13/09/2013	28	1,73	1,65	1,64	1,77	1,70	3,6
35/9,5 MPa	50	13/09/2013	28	1,25	1,16	1,29	1,3	1,25	5
35/9,5 MPa	60	13/09/2013	28	1,29	1,46	1,29	1,35	1,35	5,9

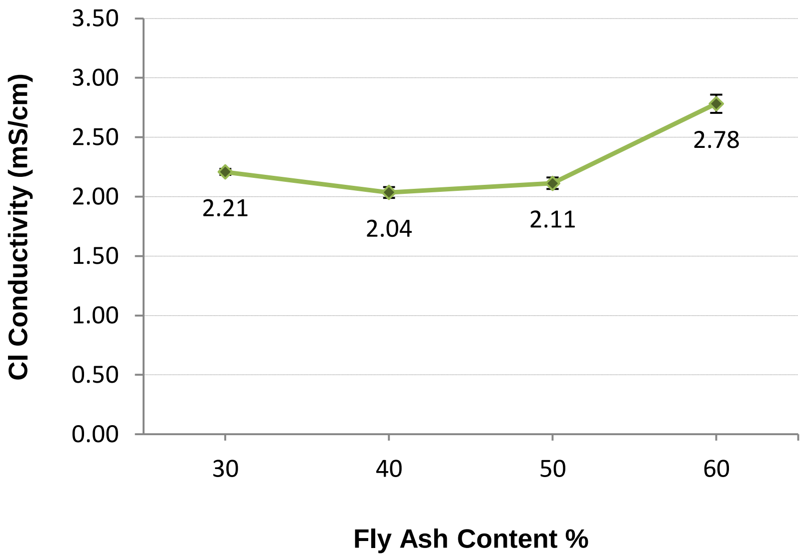


Figure 4.13: 7-days Chloride Conductivity tests analysis for the Grade 35 MPa concrete mixes.

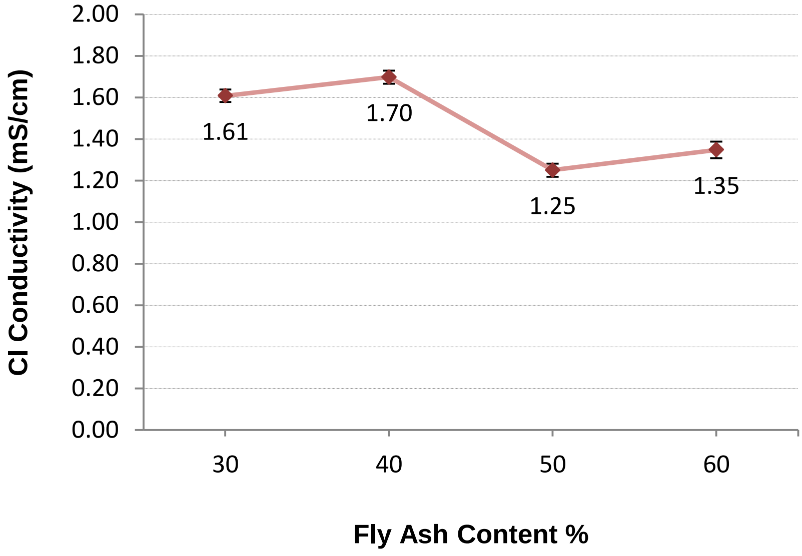


Figure 4.14: 28-days Chloride Conductivity tests analysis for the Grade 35 MPa concrete mixes.

After evaluating the durability of FA mixes, it is clear that the incorporating FA in concrete can affect the durability of concrete. The results obtained illustrate that at early stages, before the pozzolanic activity, the FA concrete has poor durability results but with time, the results improved considerable.

The overall results obtained show that although the 30% mix performed better than the high FA mixes, the concrete with high FA content have a potential of improving the durability properties in a long term. This was demonstrated by the improvement of the 50% and 60% mix in all the tests performed, especially the chloride conductivity test. The improvement in the chloride conductivity may be due to the consumption of the $Ca(OH)_2$, which results to reduced porosity, thus less migration of chemicals. The improvement of the results is expected, after 28 days of curing, as many studies show that the durability of FA concrete improves over a long period due to the pozzolanic activity that is prevalent at least after 90 days, especially the Chloride Conductivity.

4.8 Comparison between ordinary and FA concrete

For each grade of concrete mix, the cost variation is proportional to the amount of cement substitution by FA. The cost of FA varies approximately from six to 11 percent of the cost of cement, depending on whether it is unclassified or classified FA. The total price of the binder in relation to the price of cement and the percentage of the cement replaced by FA can be expressed. The cost of the binder can therefore be evaluated according to the price of equivalent cement content by using the following formula derived by Camoes, Aguiarand Jalali (2003):

$$C = B[1 - \left(\frac{0,8*FA}{B}\right)] \qquad (4.1)$$

Where:

C = Cost per m^3

B = Binder content

FA = FA content

From the materials used in the experiment the cost of the OPC was R90,00 per 50 kg bag and the cost of unclassified FA from the supplier is estimated at R100,00 per tonne. These prices don't include transportation from the manufactures which can affect the total cost of the binder. When the estimated transportation costs are added the cost of FA can be estimated between 15% to 20% of the cost of cement. Table 4.12 shows a calculated estimation of concrete cost per cube in terms of binder content.

Table 4.12: Cost comparisons for different FA substitution levels (per m^3).

Mix (MPa/%)	W/C	Water	Tot. Binder	Cement	FA	Stone	Sand	Binder Cost (unclassified)	Binder Cost (classified)
25/0	0.6	210	350.00	350.00	0.00	850	870.00	R 630.00	R 630.00
25/30	0.6	210	350.00	245.00	105.00	850	870.00	R 452.34	R 465.57
25/40	0.6	210	350.00	210.00	140.00	850	870.00	R 393.12	R 410.76
25/50	0.6	210	350.00	175.00	175.00	850	870.00	R 333.90	R 355.95
25/60	0.6	210	350.00	140.00	210.00	850	870.00	R 274.68	R 301.14
35/0	0.5	210	420.00	420.00	0.00	850	870.00	R 756.00	R 756.00
35/30	0.5	210	420.00	294.00	126.00	850	800.00	R 542.81	R 558.68
35/40	0.5	210	420.00	252.00	168.00	850	800.00	R 471.74	R 492.91
35/50	0.5	210	420.00	210.00	210.00	850	800.00	R 400.68	R 427.14
35/60	0.5	210	420.00	168.00	252.00	850	800.00	R 329.62	R 361.37
50/0	0.37	210	567.57	567.57	0.00	850	800.00	R 1 021.62	R 1 021.62
50/30	0.37	200	540.54	378.38	162.16	850	689.46	R 698.59	R 719.03
50/40	0.37	200	540.54	324.32	216.22	850	689.46	R 607.14	R 634.38
50/50	0.37	200	540.54	270.27	270.27	850	689.46	R 515.68	R 549.73
50/60	0.37	200	540.54	216.22	324.32	850	689.46	R 424.22	R 465.08

Figures 4.15 and 4.16 show the cost comparisons between the three grades of concrete mixes at four different levels of cement substitution. The figures illustrate that

the increase in FA content has a considerable effect on the cost of concrete. Concrete mixes without FA as cement substitute would cost relatively more than the mixes with FA content as a partial cement substitute, for both classified and unclassified FA.

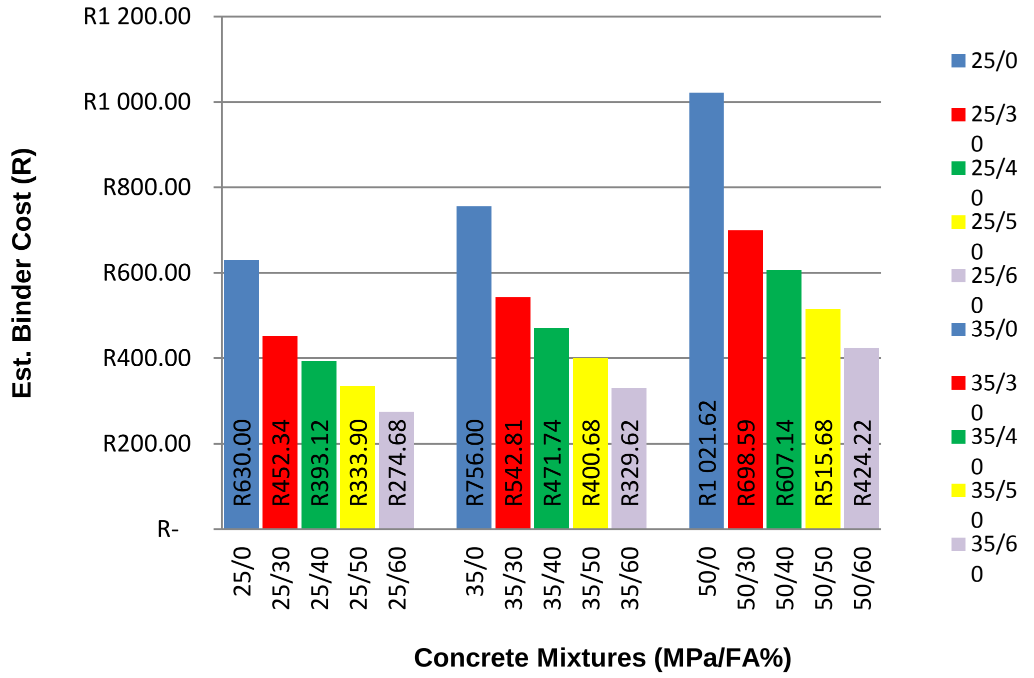


Figure 4.15: Cost comparisons for mixes with unclassified FA

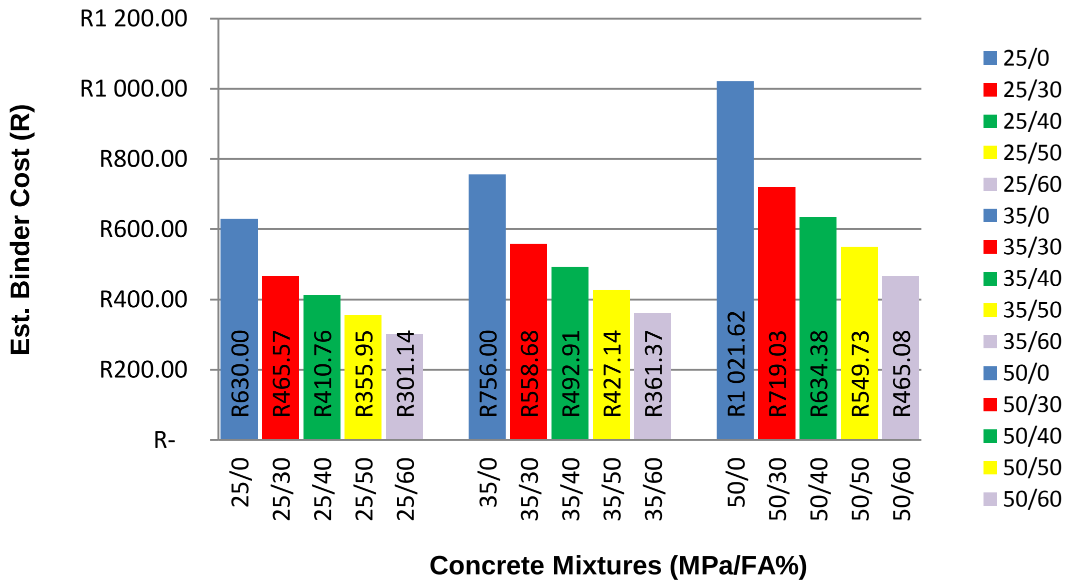


Figure 4.16: Cost comparisons for mixes with classified FA

Figure 4.17 illustrates the effect of FA content on the concrete cost, while Figure 4.18 shows a representation of the estimated binder cost per one m^3 of each grade of concrete. It can be observed from Figure 4.17 that the increase in the FA content can reduce the total cost of the mix per cubic meter, in terms of the binder. In higher W/CM mixes, the savings due to using FA as a partial substitute can range from about 26% to about 52% per cubic meter of concrete, depending on the substituted amount of cement. For lower W/CM mixes, the savings can range from 30% to 55% per cubic meter of concrete. In projects where large quantities of concrete are utilised, there would be significant amounts of savings made in terms of concrete costs.

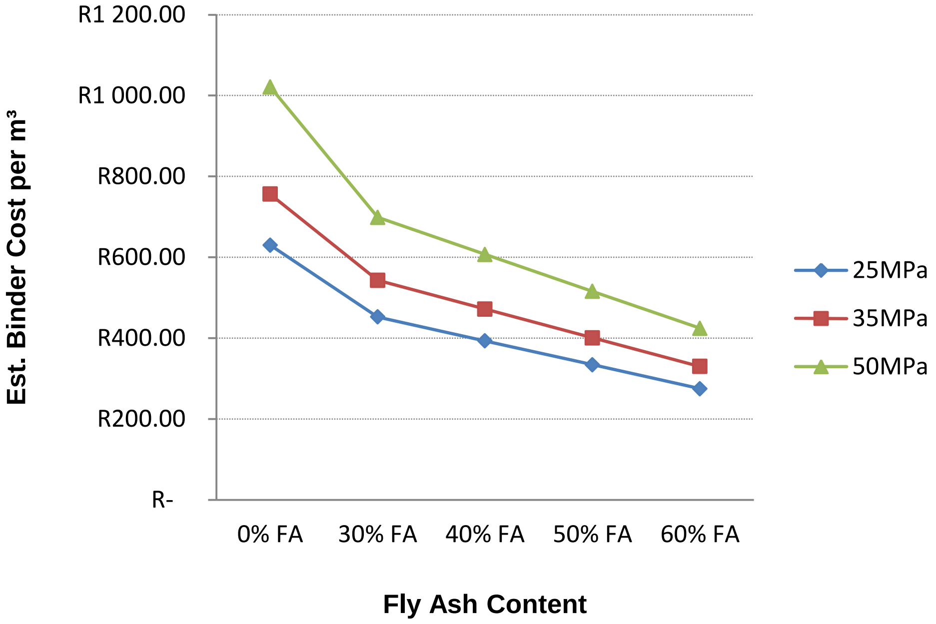


Figure 4.17: Estimated cost of binder for concrete with different FA volumes.

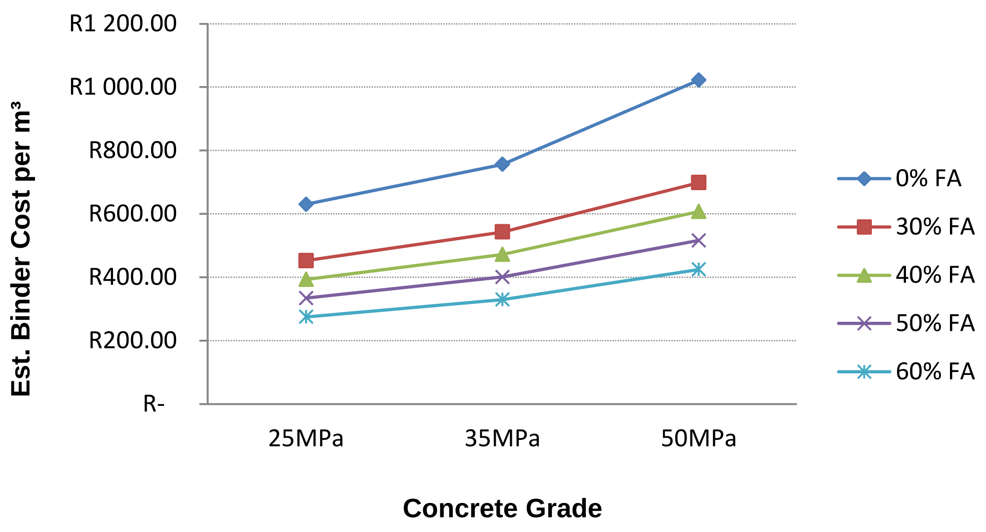


Figure 4.18: Estimated cost of binder for different grades of concrete with different FA volumes.

Figure 4.18 illustrates that the lower grades of concrete cost less than the higher grades of concrete with similar constituents. It is noted that the cost of grade 25 MPa concrete without FA can cost more than grade 35 MPa concrete with FA at all four levels of cement substitutions and more than the 50 MPa with 40%, 50% and 60% substitutions of cement. Also the grade 35 MPa concrete with no FA can cost more than grade 50 MPa concrete at all four levels of FA substitution. Although the decision of choosing the type of concrete depends on other requirements and properties such as compressive strength and durability, the cost of concrete does play a big role in choosing what type of concrete to use.

4.9 Conclusion

After testing concrete specimens and evaluating their performance on certain plastic and hardened properties, the results show that the amount of FA that is used in concrete mixes does affect most of the concrete properties. As some previous studies have shown that the utilization of FA at higher levels in concrete affects the concrete properties positively in most occasions, the results obtained in this study illustrated that can be true in many cases. The results show that the control mixes of 30% FA performed better than the higher volume FA mixes in many cases, however the performance of the 40% and 50% FA mixes was satisfactory, and compatible to the 30% FA mixes in some cases.

The evaluation of the slump, air content, and drying shrinkage show that the 30%, 40% and 50% grade 35 MPa mixes performed similar. As was expected, the setting time of the grade 35 MPa mixes increased with the increase of FA. When testing all three grades of 25 Mpa, 35 MPa and 50 MPa concrete for compressive strength, the mixes with the lower FA content attained higher strengths in all cases. The higher volume FA mixes attained acceptable strengths after 28 days of curing and continued to gain more strength even after one year. For the 0,6 W/CM concrete the 40% and 50% mixes performed similarly while for the 0,5 W/CM concrete the 40% mix performed similar to the 30% mix. For the 0,37 W/CM concrete the 40%, 50% and 60% mixes performed comparable.

When evaluating the durability properties for the grade 35 MPa concrete at four FA substitution levels, the results illustrate that at early stages (after 7 days of moist curing) the 30% FA mix had better durability qualities when testing for Oxygen Permeability and Water Sorptivity while the 40% had better Chloride Conductivity results. At later stages the durability qualities for the higher FA mixes improved considerable after 28 days where the 40% mix performed comparable to the 30% mix for the OPI. The 30% mix had better sorptivity qualities than the other mixes, however they improved considerably. The evaluation of the Chloride Conductivity index illustrated that the 50% mix had better qualities than all the mixes, followed closely by the 60% mix. These results support the previous studies which found that replacement of cement with more than 50% FA results in much improved Chloride Conductivity qualities (Chalee, Ausapanit and Jaturapitakkul, 2010, Kayali and Ahmed, 2013, and Gu et al., 1999). This shows that the addition of FA can improve the permeability of concrete, making it less susceptible to chemical attacks. Although some results fell outside the acceptable levels, however after 28 days, the improvement shown at later stages proves that with time the HVFA concrete will gain very good durability qualities, due to the pozzolanic activity.

The tests performed gave reliable and realistic results, although there were negligible problems with a few results such as the recording of the start of setting time with the 40% mix, this did not affect the overall test results. The evaluation of the different concrete properties shows that FA can partially substitute the cement at 40% and perform comparable to the 30% FA concrete. Also the 50% FA mix can produce favourable concrete with acceptable compressive strength and good chloride conductivity qualities. The conclusion and recommendations reached from the laboratory work are discussed in the following chapter.

CHAPTER 5

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

After evaluating the performance of FA concrete, by performing various tests on fresh and hardened concrete of different grades and varying levels of FA content, it was noted that FA affects the properties and characteristics of concrete. The following conclusions were reached after analyzing the laboratory tests results:

1. The results from the slump tests for the 35 MPa FA mixes showed that the mixes with higher FA content had higher slump than the control, 30% FA, mix. The 40% and the 50% mixes attained equal slumps of 85 mm, compared to the 70 mm achieved by the 30% FA mix. This proves that the addition of FA does improve the workability and consistency of the concrete mixes. This would be due to the spherical shape of FA particles, which creates a ball-bearing effect thus making the concrete more workable. Concrete with high FA volume can be beneficial for pump mixes as the desired slumps can be achieved with lesser water and plasticizers.

2. The increase in FA content had a negligible effect on the air content in the concrete. The FA mixes had calculated air content between 2% and 2,2% compared to the ordinary concrete, which had 0,5% air content. This shows that the presence of FA does affect the air content of concrete, however the increase of FA content might not necessary increase the air content.

3. When evaluating the drying shrinkage, the 28-days results showed that the shrinkage increased with the increase of FA content. The lowest FA mix had the lowest shrinkage percentage at 0,045% and the highest FA mix had the highest percentage at 0,056%. All the mixes had reasonable drying shrinkage.

4. Increasing the FA volume resulted in prolonged setting times. The ordinary concrete took about one hour and 45 min to set and the FA mixes took between two and four hours. This means that the increase in FA slowed down the rate of hydration as expected. This is not desirable in some concrete applications, however it can welcomed in certain concreting situations where more time is

required for working with concrete. The longer setting time reduces the need for utilizing admixes such as retarders. When concreting in hot temperatures, the higher FA volume concrete can be very desirable. Also in mass concreting cases, the heat reduction is a welcomed attribute as it keeps the concrete temperatures at acceptable levels.

5. When compressive strength was evaluated, the concrete mixes with low FA (30%) attained higher strengths, especially at early ages, than the concrete mixes with higher FA content. All the mixes gained acceptable compressive strength after 28 days and the strength continued to increase over the period of one year. The grade 35 MPa concrete with 40% FA got compressive strength that is very compatible with the 30% mix. Although the 50% FA mixes for all three grades of concrete got lower compressive strengths than the 30% mixes, they attained good results. Also the 60% FA mixes attained acceptable compressive strength in all cases. This shows that concrete can gain acceptable compressive strength even if the cement content is less than of FA. The strength development after 28 days was constant for most of the mixes.

6. The evaluation of concrete durability qualities shows that increasing the FA in the concrete mixes can affect the durability of concrete negatively at early stages but improve with time. The control mix with the lowest FA volume has better OPI and Water Sorptivity qualities, while the 50% mix had the best chloride conductivity qualities, followed by the 60% FA mix. FA is well recognized to have good chloride conductivity traits so it was expected that the higher FA mixes would attain good results. The durability qualities are expected to continue to improve over time due pozzolanic activity.

7. The cost comparison exercise shows that substituting cement with FA can reduce the materials cost of the concrete considerably. The increase in FA volumes decreases the cost of cement, thus of the concrete. A grade 50 MPa concrete with FA volume more than 40% could cost less than a grade 25 MPa OPC concrete. The overall cost can be further reduced, due to less demand for water and admixes to improve workability.

8. The results from this study show that FA can substitute cement beyond 30% and still result in concrete with good properties. The compressive strength results for the 50% mixes show that the compressive strength of concrete is not compromised by the increase, and the evaluation of durability qualities shows that the 40% and 50% FA mixes can perform as good as the 30% FA concrete and even better when it comes to chloride conductivity. The utilization of FA in concrete can be optimized by increasing the volume of FA to 50% of the binder volume, and result in good concrete and have considerable cost savings.

9. The outcomes from this study are relevant to the current trends in the South African construction industry, as there is a growing interest in optimizing the utilization of FA content in concrete for different benefits. The projects such as the construction of the De Hoop Dam in Limpopo, South Africa, saw the utilization of FA up to 72% with resounding success, technically and economically (van Niekerk, 2014). ESKOM is also working on optimizing the amount of FA that is utilized commercially instead of disposing it to landfills (Singh, 2016).

5.2 Recommendations

This study on concrete with higher FA content has elucidated how FA affects concrete properties. Arising from this study the following recommendations can be made:

1. Designers and engineers should endorse the utilization of higher FA content in concrete, beyond 30%, to increase awareness of its benefits and its usage in the industry, especially in the transport discipline where large amounts of concrete are utilized.

2. Professional incentive initiatives such as LEED should be set up by government departments or professional organizations such as Concrete Society of Southern Africa to give ratings points for companies that promote responsible engineering design.

3. Further research, especially in South Africa, on FA concrete products should be encouraged to improve on current trends and construction methods.

4. Other durability testing methods such as for carbonation should be introduced and standardized in South Africa to ensure that the performance of concrete with FA is properly evaluated for all possible circumstances that can affect structures adversely.

5. The correlation between the three durability indexes should be extensively studied to ascertain the relevance of each test to the others, as there seems to be no conclusive connection in the results that are usually obtained.

6. The incorporation of FA in non-structural concrete works should be exercised to promote sustainable development and responsible construction practices.

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APPENDICES

Appendix A: Sieve Analysis for Fine Aggregates

FINE AGGREGATES SIEVE ANALYSIS: Sample no. 1

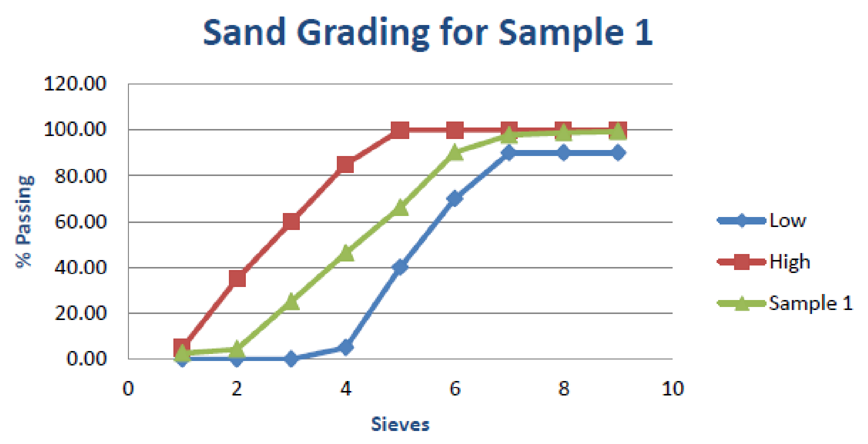
Date: 03/ 05/ 2013
Pan No.: NQU
Material: River sand
Dry Sample mass (g): 797.4

Sieve Apeture (mm)	Mass Retained (g)	% Retained	% Passing	Cumulative % Retained
4.75	5.3	0.66	99.34	0.66
3.35	4	0.50	98.83	
2.36	8.7	1.09	97.74	2.26
1.18	59.7	7.49	90.26	9.74
0.600	191.4	24.00	66.25	33.75
0.425	158.8	19.91	46.34	
0.300	168.7	21.16	25.18	74.82
0.150	165.8	20.79	4.39	95.61
0.075	14.5	1.82	2.57	
<0.075	20.5	2.57	0.00	
Total	**797.4**	**100.00**	**-**	**216.84**

Fineness Modulus= $\frac{\Sigma \text{ Cum. \% Ret}}{100}$

Fineness Modulus= $\frac{216.84}{100}$

F.M = 2.17



FINE AGGREGATES SIEVE ANALYSIS: Sample no. 2

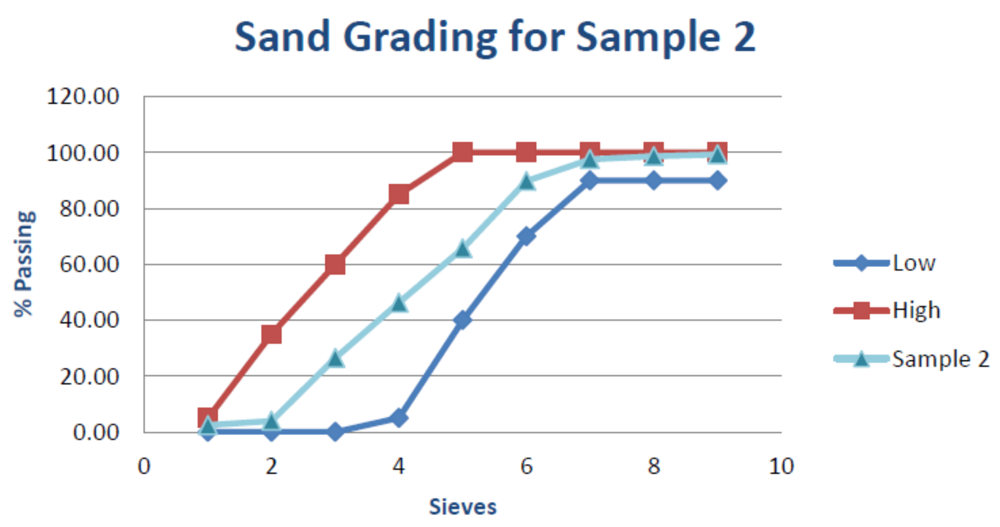
Date: 03/ 05/ 2013
Pan No.: NX
Material: River sand
Dry Sample mass (g): 743.6

Sieve Apeture (mm)	Mass Retained (g)	% Retained	% Passing	Cumulative % Retained
4.75	5.1	0.69	99.31	0.69
3.35	4.7	0.63	98.68	
2.36	8.1	1.09	97.59	2.41
1.18	58	7.80	89.79	10.21
0.600	178.9	24.06	65.73	34.27
0.425	144.4	19.42	46.32	
0.300	147	19.77	26.55	73.45
0.150	167.8	22.57	3.98	96.02
0.075	11.8	1.59	2.39	
<0.075	17.8	2.39	0.00	
Total	**743.6**	**100.00**	**-**	**217.04**

Fineness Modulus= $\frac{\Sigma \text{ Cum. \% Ret}}{100}$

Fineness Modulus= $\frac{217.04}{100}$

F.M = **2.17**



FINE AGGREGATES SIEVE ANALYSIS: Sample no. 3

Date: 03/ 05/ 2013
Pan No.: 1234
Material: River sand
Dry Sample mass (g): 443.7

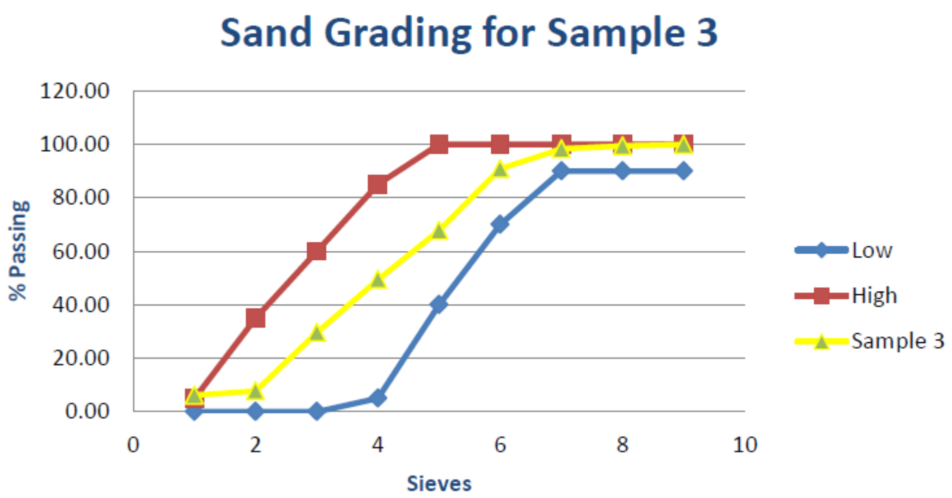
Sieve Apeture (mm)	Mass Retained (g)	% Retained	% Passing	Cumulative % Retained
4.75	0.8	0.18	99.82	0.18
3.35	2.2	0.50	99.32	
2.36	4.8	1.08	98.24	1.76
1.18	32.9	7.41	90.83	9.17
0.600	102.3	23.06	67.77	32.23
0.425	81.5	18.37	49.40	
0.300	88	19.83	29.57	70.43
0.150	96.9	21.84	7.73	92.27
0.075	6.9	1.56	6.18	
<0.075	27.4	6.18	0.00	
Total	**443.7**	**100.00**	**-**	**206.04**

Fineness Modulus= $\frac{\Sigma \text{ Cum. \% Ret}}{100}$

Fineness Modulus= $\frac{206.04}{100}$

F.M = **2.06**

Av F.M = **2.13**



Appendix B: Sieve Analysis for Coarse Aggregates

COARSE AGGREGATES SIEVE ANALYSIS: Sample no 1

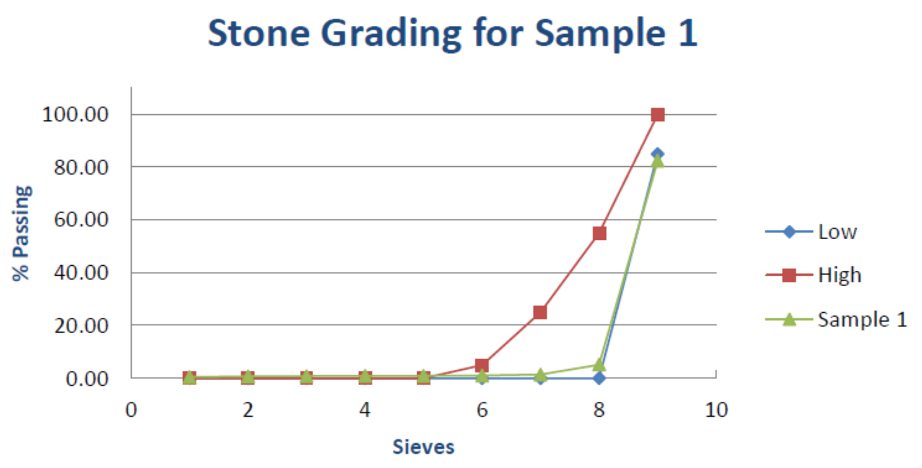
Date: 03/ 05/ 2013
Pan No.: C
Material: 9,5mm Stone
Dry Sample mass (g): 1087.1

Sieve Apeture (mm)	Mass Retained (g)	% Retained	% Passing
19.00	-	-	-
13.2	-	-	-
9.5	191.1	17.58	82.42
6.7	840.3	77.30	5.12
4.75	40.8	3.75	1.37
2.36	4.3	0.40	0.98
1.18	0.9	0.08	0.89
0.600	0.5	0.05	0.85
0.300	0.7	0.06	0.78
0.150	1.2	0.11	0.67
0.075	2.5	0.23	0.44
<0.075	4.8	0.44	
Total	**1087.1**	**100.00**	

$$\text{Fineness Modulus} = \frac{\Sigma \text{ Cum. \% Ret}}{100}$$

$$\text{Fineness Modulus} = \frac{906.48}{100}$$

F.M = **9.06**



COARSE AGGREGATES SIEVE ANALYSIS: Sample no. 2

Date: 03/ 05/ 2013
Pan No.: M
Material: 9,5mm Stone
Dry Sample mass (g): 1127.5

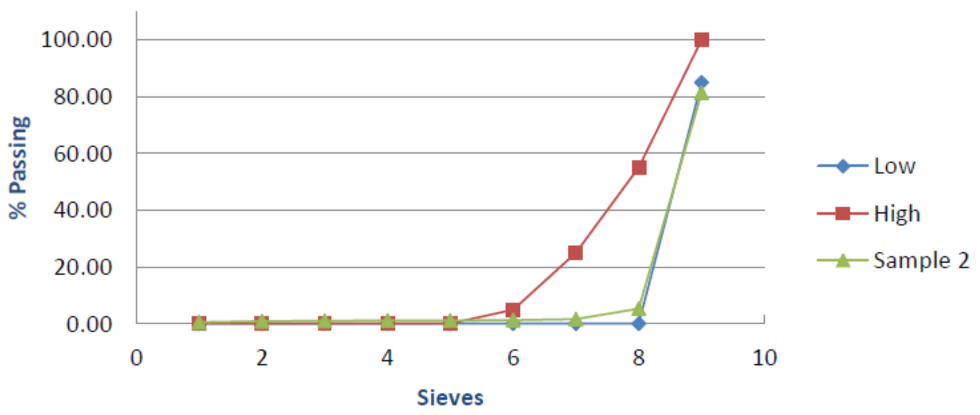
Sieve Apeture (mm)	Mass Retained (g)	% Retained	% Passing
19.00	-	-	-
13.2	-	-	-
9.5	210.3	18.65	81.35
6.7	857.3	76.04	5.31
4.75	42.4	3.76	1.55
2.36	3.6	0.32	1.23
1.18	0.9	0.08	1.15
0.600	0.6	0.05	1.10
0.300	0.9	0.08	1.02
0.150	1.6	0.14	0.88
0.075	3.4	0.30	0.58
<0.075	6.5	0.58	
Total	**1127.5**	**100.00**	

Fineness Modulus= Σ Cum. % Ret / 100

Fineness Modulus= 805.83 / 100

F.M = **8.06**

Stone Grading for Sample 2



COARSE AGGREGATES SIEVE ANALYSIS: Sample no. 3

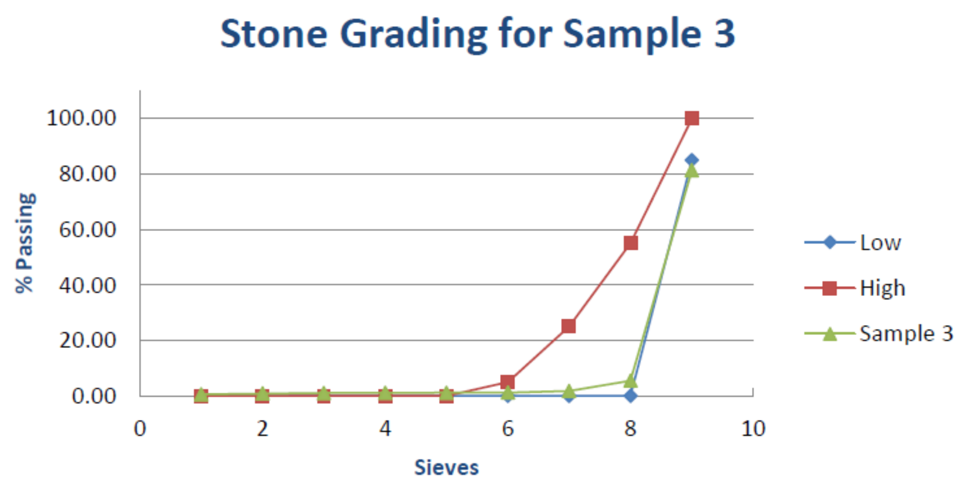
Date: 03/ 05/ 2013
Pan No.: 90
Material: 9,5mm Stone
Dry Sample mass (g): 1034.2

Sieve Apeture (mm)	Mass Retained (g)	% Retained	% Passing
19.00	-	-	-
13.2	-	-	-
9.5	192.8	18.64	81.36
6.7	784.8	75.88	5.47
4.75	38.7	3.74	1.73
2.36	5.2	0.50	1.23
1.18	0.7	0.07	1.16
0.600	0.5	0.05	1.11
0.300	0.9	0.09	1.02
0.150	1.6	0.15	0.87
0.075	2.9	0.28	0.59
<0.075	6.1	0.59	
Total	**1034.2**	**100.00**	

Fineness Modulus= $\frac{\Sigma \text{ Cum. \% Ret}}{100}$

Fineness Modulus= $\frac{805.45}{100}$

F.M = **8.05**



Appendix C: Fly Ash Oxide Analysis

AshResources
Fly ash products

ASH RESOURCES (PTY) LIMITED
REG. NO. 1975/000746/07

SABS
ISO 9001

P O Box 3017 RANDBURG 2125
SOUTH AFRICA

35 Westfield Road
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FAX : (011) 657 2334
FAX : (011) 657 2329 Logistics
WEB: www.ashresources.co.za

Oxide Analysis

Matla DurapozzPro																	
Sample	Units	SiO2	Al2O3	Fe2O3	CaO	MgO	K2O	Na2O	TiO2	Mn2O3	P2O5	Cr2O3	SrO	SO3	LOI @ 950°C	Sum: SiO2, Al203 & FeO3	Total oxide
March 13/220/1	%	53.19	30.12	2.60	5.74	1.93	0.84	0.57	1.65	0.03	0.16	0.00	0.25	0.73	1.25	85.91	99.07

Appendix D: Compressive Strength Test Results for the Trial Mixes

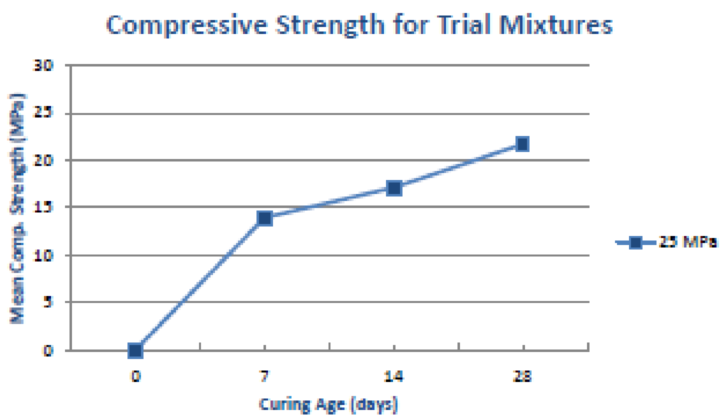
CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Trial Concrete Mixtures
Mix Description	25MPa/9,5 - 30%FA

Specimen Number	25/1	25/2	25/3	25/4	25/5	25/6	25/7	25/8	25/9
Cast Date	10/05/2013			10/05/2013			10/05/2013		
Test Date	17/05/2013			24/05/2013			07/06/2013		
Age of Specimen (days)	7	7	7	14	14	14	28	28	28
Specified Strength (Mpa)	16.25			22.5			25		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	100	100	100	99	101	101	100	100	100
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.356	2.367	2.345	2.312	2.37	2.391	2.402	2.344	2.354
Gauge Reading (kN)	150.1	128.5	139.6	162.8	176.1	176.7	207.9	222.7	220.6
Density (kg/m^3)	2356	2367	2345	2335	2347	2367	2402	2344	2354
Compressive Strength (Mpa)	15.0	12.9	14.0	16.4	17.4	17.5	20.79	22.27	22.06
Mean Compressive Strength (Mpa)	14			17.1			21.7		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: Cube results have failed to meet the required strength at 28 days.
The concrete mix design needs to be ammended

Laboratory Technician: Sabelo Zulu   Date: 07/06/2013



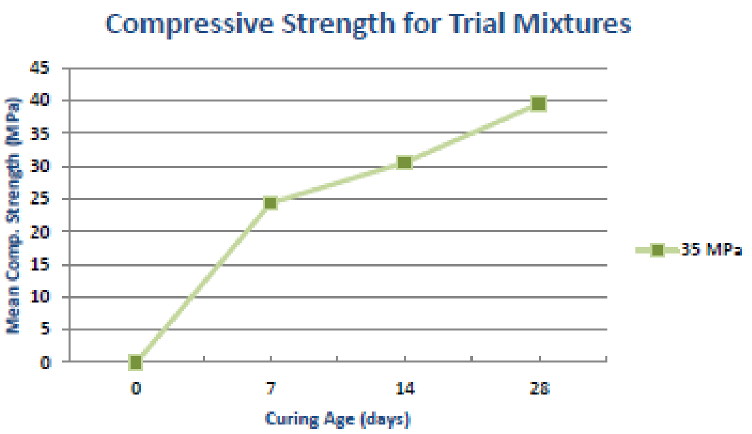
CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Trial Concrete Mixtures
Mix Description	35MPa/9,5 - 30%FA

Specimen Number	35/1	35/2	35/3	35/4	35/5	35/6	35/7	35/8	35/9
Cast Date	10/05/2013			10/05/2013			10/05/2013		
Test Date	17/05/2013			24/05/2013			07/06/2013		
Age of Specimen (days)	7	7	7	14	14	14	28	28	28
Specified Strength (Mpa)	22.75			31.5			35		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	100	101	100	100	102	103	100	100	100
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.385	2.374	2.491	2.336	2.445	2.452	2.401	2.438	2.43
Gauge Reading (kN)	235.2	249.3	248.2	307.4	314.9	310.1	393.1	390.3	402.4
Density (kg/m^3)	2385	2350	2491	2336	2397	2381	2401	2438	2430
Compressive Strength (Mpa)	23.5	24.7	24.8	30.7	30.9	30.1	39.31	39.03	40.24
Mean Compressive Strength (Mpa)	24.3			30.6			39.5		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: Concrete mix passed

Laboratory Technician: Sabelo Zulu **Date:** 07/06/2013



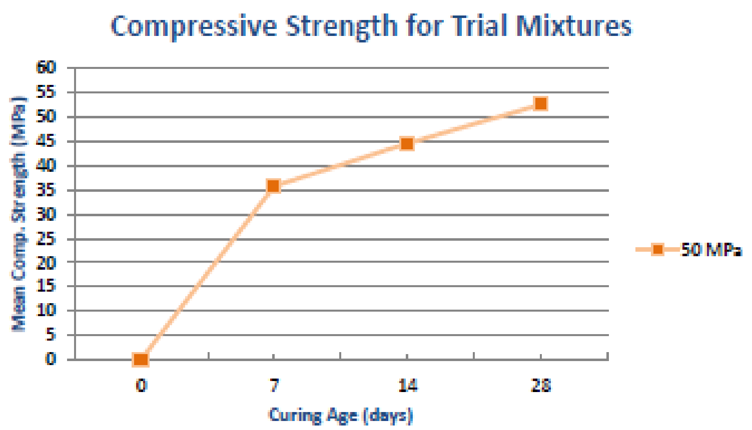
CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Trial Concrete Mixtures
Mix Description	50MPa/9,5 - 30%FA

Specimen Number	50/1	50/2	50/3	50/4	50/5	50/6	50/7	50/8	50/9
Cast Date	10/05/2013			10/05/2013			10/05/2013		
Test Date	17/05/2013			24/05/2013			07/06/2013		
Age of Specimen (days)	7	7	7	14	14	14	28	28	28
Specified Strength (Mpa)	32.5			45			50		
Dimension 1 (mm)	100	100	100	101	100	100	100	100	100
Dimension 2 (mm)	100	100	100	100	100	100	101	100	101
Dimension 3 (mm)	100	100	100	100	101	100	100	100	100
Mass (kg)	2.425	2.468	2.502	2.466	2.389	2.432	2.447	2.45	2.422
Gauge Reading (kN)	344.8	354	375.5	444.4	458	440.2	516.5	533.6	539.8
Density (kg/m^3)	2425	2468	2502	2442	2365	2432	2423	2450	2398
Compressive Strength (Mpa)	34.5	35.4	37.6	44	45.8	44.0	51.14	53.36	53.45
Mean Compressive Strength (Mpa)	35.8			44.6			52.6		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: Concrete mix passed

Laboratory Technician: Sabelo Zulu Date: 07/06/2013



Appendix E: Compressive Strength Test Results for Test Mixes

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 30%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	11/09/2013			11/09/2013			11/09/2013		
Test Date	12/09/2013			18/09/2013			25/09/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	99	100	100	100	100	100	100	100
Dimension 2 (mm)	100	101	101	100	100	100	100	98	99
Dimension 3 (mm)	98	100	100	99	99	100	100	100	100
Mass (kg)	2.322	2.356	2.331	2.341	2.342	2.359	2.356	2.321	2.331
Gauge Reading (kN)	0	26.3	23.6	136.1	148.4	142.4	205.2	216.7	210.4
Density (kg/m^3)	2369	2356	2308	2365	2366	2359	2356	2368	2355
Compressive Strength (Mpa)	0.00	2.63	2.36	13.61	14.84	14.24	20.52	21.67	21.04
Mean Compressive Strength (Mpa)	**2.5**			**14.2**			**21.1**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: Cube no. 001 crumbled and recorded no strength

Laboratory Technician: Emmanuel Makhathini and Sabelo Zulu Date: 25/09/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 30%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	11/09/2013			11/09/2013			11/09/2013		
Test Date	09/10/2013			06/11/2013			04/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	25			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	100	100	99	98	98	99	100	99	100
Dimension 3 (mm)	100	100	100	100	100	100	100	101	100
Mass (kg)	2.384	2.384	2.333	2.321	2.326	2.344	2.394	2.368	2.382
Gauge Reading (kN)	334.9	312.4	314.3	435.1	415.8	439.3	458.1	451	489
Density (kg/m^3)	2384	2384	2357	2368	2373	2368	2394	2368	2382
Compressive Strength (Mpa)	33.49	31.24	31.43	43.51	41.58	43.93	45.81	45.10	48.90
Mean Compressive Strength (Mpa)	**32.1**			**43.0**			**46.6**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28-day results acceptable

Laboratory Technician: Sabelo Zulu Date: 04/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 30%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	11/09/2013			11/09/2013					
Test Date	10/03/2014			11/09/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	100	100			
Dimension 2 (mm)	101	99	98	100	100	99			
Dimension 3 (mm)	100	100	100	100	100	100			
Mass (kg)	2.386	2.37	2.36	2.41	2.4	2.378			
Gauge Reading (kN)	463.6	451.6	479.9	484.6	488.7	489			
Density (kg/m^3)	2362	2394	2408	2410	2400	2402			
Compressive Strength (Mpa)	46.36	45.16	47.99	48.46	48.87	48.90			
Mean Compressive Strength (Mpa)	**46.5**			**48.7**					
Comments	Cured in water			Cured in water					

Remarks: Results acceptable

Laboratory Technician: Sabelo Zulu Date: 11/09/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 40%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	20/09/2013			20/09/2013			20/09/2013		
Test Date	21/09/2013			27/09/2013			04/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	100	100	100	100	99	100	101	99	99
Dimension 3 (mm)	100	98	99	100	100	100	100	100	100
Mass (kg)	2.131	2.263	2.294	2.362	2.336	2.339	2.371	2.338	2.331
Gauge Reading (kN)	22.2	23	22.7	149.1	130.2	146	173	189.3	192.9
Density (kg/m^3)	2131	2309	2317	2362	2360	2339	2348	2362	2355
Compressive Strength (Mpa)	2.22	2.30	2.27	14.91	13.02	14.60	17.30	18.93	19.29
Mean Compressive Strength (Mpa)	**2.3**			**14.2**			**18.5**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

Laboratory Technician: Sabelo Zulu   Date: 04/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 40%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	20/09/2013			20/09/2013			20/09/2013		
Test Date	18/10/2013			15/11/2013			13/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	25			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	99	100	100	100	99	100	101	99	99
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.342	2.34	2.352	2.346	2.352	2.357	2.351	2.341	2.356
Gauge Reading (kN)	268.9	271.1	263.1	347.7	349.9	367.8	391.4	374.7	375
Density (kg/m^3)	2366	2340	2352	2346	2376	2357	2328	2365	2380
Compressive Strength (Mpa)	26.89	27.11	26.31	34.77	34.99	36.78	39.14	37.47	37.50
Mean Compressive Strength (Mpa)	**26.8**			**35.5**			**38.0**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results acceptable

Laboratory Technician: Sabelo Zulu Date: 13/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 40%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	20/09/2013			20/09/2013					
Test Date	19/03/2014			20/09/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	99	100			
Dimension 2 (mm)	100	101	100	101	100	101			
Dimension 3 (mm)	100	100	100	100	99	100			
Mass (kg)	2.342	2.38	2.351	2.378	2.337	2.381			
Gauge Reading (kN)	393.2	419.1	376	398.1	413.3	424.1			
Density (kg/m^3)	2342	2356	2351	2354	2384	2357			
Compressive Strength (Mpa)	39.32	41.91	37.60	39.81	41.33	42.41			
Mean Compressive Strength (Mpa)	**39.6**			**41.2**					
Comments	Cured in water			Cured in water					

Remarks: Results acceptable

Laboratory Technician: Sabelo Zulu   Date: 20/09/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 50%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	03/10/2013			03/10/2013			03/10/2013		
Test Date	04/10/2013			10/10/2013			17/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	99	98	99	100	99	100	98	99	99
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.261	2.242	2.247	2.277	2.281	2.28	2.257	2.265	2.26
Gauge Reading (kN)	19	19.7	19	114	119	116.7	184.6	184.8	188.6
Density (kg/m^3)	2284	2288	2270	2277	2304	2280	2303	2288	2283
Compressive Strength (Mpa)	1.90	1.97	1.90	11.40	11.90	11.67	18.46	18.48	18.86
Mean Compressive Strength (Mpa)	**1.9**			**11.7**			**18.6**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

Laboratory Technician: Sabelo Zulu Date: 17/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 50%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	03/10/2013			03/10/2013			03/10/2013		
Test Date	31/10/2013			28/11/2013			26/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	25			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	99	98	99	99	98	98	99	98	99
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.248	2.257	2.278	2.271	2.253	2.263	2.28	2.268	2.28
Gauge Reading (kN)	272.4	250.4	265.7	350	342	350.8	350.5	365.1	391.3
Density (kg/m^3)	2271	2303	2301	2294	2299	2309	2303	2314	2303
Compressive Strength (Mpa)	27.24	25.04	26.57	35.00	34.20	35.08	35.05	36.51	39.13
Mean Compressive Strength (Mpa)	**26.3**			**34.8**			**36.9**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results acceptable

Laboratory Technician: Sabelo Zulu Date: 26/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 50%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	03/10/2013			03/10/2013					
Test Date	01/04/2014			03/10/2013					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	100	100			
Dimension 2 (mm)	99	98	99	98	100	100			
Dimension 3 (mm)	100	100	100	100	100	100			
Mass (kg)	2.284	2.244	2.284	2.264	2.28	2.289			
Gauge Reading (kN)	413	416.7	434.2	440.9	405.5	439.4			
Density (kg/m^3)	2307	2290	2307	2310	2280	2289			
Compressive Strength (Mpa)	41.30	41.67	43.42	44.09	40.55	43.94			
Mean Compressive Strength (Mpa)	**42.1**			**42.9**					
Comments	Cured in water			Cured in water					

Remarks: Results acceptable

Laboratory Technician: Sabelo Zulu   Date: 03/10/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 60%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	09/10/2013			09/10/2013			09/10/2013		
Test Date	10/10/2013			16/10/2013			23/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	99	100	100	100	101	100
Dimension 2 (mm)	101	100	100	102	101	100	99	102	100
Dimension 3 (mm)	100	100	100	101	100	100	100	100	100
Mass (kg)	2.284	2.276	2.279	2.324	2.266	2.266	2.251	2.315	2.289
Gauge Reading (kN)	14.5	14.9	13	80.1	85.3	80.1	125.1	126.2	130.7
Density (kg/m^3)	2261	2276	2279	2279	2244	2266	2274	2247	2289
Compressive Strength (Mpa)	1.45	1.49	1.30	8.01	8.53	8.01	12.51	12.62	13.07
Mean Compressive Strength (Mpa)	**1.4**			**8.2**			**12.7**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

....

Laboratory Technician: Sabelo Zulu Date: 23/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 60%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	09/10/2013			09/10/2013			09/10/2013		
Test Date	06/11/2013			04/12/2013			01/01/2014		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	25			-			-		
Dimension 1 (mm)	99	100	101	100	100	100	100	100	100
Dimension 2 (mm)	101	99	103	103	102	101	101	101	102
Dimension 3 (mm)	99	101	99	100	100	100	100	101	100
Mass (kg)	2.299	2.269	2.359	2.318	2.314	2.297	2.304	2.291	2.328
Gauge Reading (kN)	225.2	224.3	240.6	271.5	324.4	279.8	290.1	268.6	269.9
Density (kg/m^3)	2322	2269	2291	2250	2269	2274	2281	2246	2282
Compressive Strength (Mpa)	22.52	22.43	24.06	27.15	32.44	27.98	29.01	26.86	26.99
Mean Compressive Strength (Mpa)	**23.0**			**29.2**			**27.6**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results did not meet the requirements
56 day results acceptable

Laboratory Technician: Sabelo Zulu Date: 01/01/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	25MPa/9,5 - 60%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	09/10/2013			09/10/2013					
Test Date	07/04/2014			09/10/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	100	100			
Dimension 2 (mm)	99	100	99	99	99	98			
Dimension 3 (mm)	100	100	100	100	101	100			
Mass (kg)	2.273	2.26	2.284	2.299	2.286	2.293			
Gauge Reading (kN)	285.7	286.2	319.5	323.9	321.4	327.1			
Density (kg/m^3)	2296	2260	2307	2322	2286	2340			
Compressive Strength (Mpa)	28.57	28.62	31.95	32.39	32.14	32.71			
Mean Compressive Strength (Mpa)	**29.7**			**32.4**					
Comments	Cured in water			Cured in water					

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu Date: 09/10/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 30%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	12/09/2013			12/09/2013			12/09/2013		
Test Date	13/09/2013			19/09/2013			26/09/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	100	100	100	101	100	100	99	100	102
Dimension 3 (mm)	100	100	100	100	98	100	100	100	100
Mass (kg)	2.33	2.35	2.306	2.397	2.324	2.354	2.331	2.355	2.411
Gauge Reading (kN)	16	18	18	195.6	197	173	286.2	300.5	313.3
Density (kg/m^3)	2330	2350	2306	2373	2371	2354	2355	2355	2364
Compressive Strength (Mpa)	1.60	1.80	1.80	19.56	19.70	17.30	28.62	30.05	31.33
Mean Compressive Strength (Mpa)	**1.7**			**18.9**			**30.0**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

....

Laboratory Technician: Sabelo Zulu Date: 26/09/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 30%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	12/09/2013			12/09/2013			12/09/2013		
Test Date	10/10/2013			07/11/2013			05/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	35			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	100	100	100	101	100	99	100	101	101
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.418	2.401	2.398	2.407	2.39	2.354	2.398	2.39	2.409
Gauge Reading (kN)	421.3	433.8	432.1	534.9	550.2	522.5	569	551.6	610.2
Density (kg/m^3)	2418	2401	2398	2383	2390	2378	2398	2366	2385
Compressive Strength (Mpa)	42.13	43.38	43.21	53.49	55.02	52.25	56.90	55.16	61.02
Mean Compressive Strength (Mpa)	**42.9**			**53.6**			**57.7**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results acceptable

Laboratory Technician: Sabelo Zulu Date: 05/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 30%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	12/09/2013			12/09/2013					
Test Date	11/03/2014			11/09/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	100	100			
Dimension 2 (mm)	100	100	101	101	100	101			
Dimension 3 (mm)	100	100	100	100	100	100			
Mass (kg)	2.391	2.394	2.408	2.416	2.375	2.428			
Gauge Reading (kN)	530.5	580.5	566.7	631.2	573.6	613			
Density (kg/m^3)	2391	2394	2384	2392	2375	2404			
Compressive Strength (Mpa)	53.05	58.05	56.67	63.12	57.36	61.30			
Mean Compressive Strength (Mpa)	**55.9**			**60.6**					
Comments	Cured in water			Cured in water					

Remarks: Results acceptable

Laboratory Technician: Sabelo Zulu Date: 11/09/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 40%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	23/09/2013			23/09/2013			23/09/2013		
Test Date	24/09/2013			30/09/2013			07/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	101	100	100	100	100	100	100	100	100
Dimension 2 (mm)	99	100	102	100	100	101	100	100	101
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.301	2.379	2.357	2.35	2.378	2.367	2.365	2.37	2.379
Gauge Reading (kN)	17.8	17.8	18.3	173	179.3	167.2	272.3	270.6	287.4
Density (kg/m^3)	2301	2379	2311	2350	2378	2344	2365	2370	2355
Compressive Strength (Mpa)	1.78	1.78	1.83	17.30	17.93	16.72	27.23	27.06	28.74
Mean Compressive Strength (Mpa)	**1.8**			**17.3**			**27.7**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

Laboratory Technician: Sabelo Zulu   Date: 07/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 40%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	23/09/2013			23/09/2013			23/09/2013		
Test Date	21/10/2013			18/11/2013			16/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	35			-			-		
Dimension 1 (mm)	100	100	100	100	102	100	100	100	100
Dimension 2 (mm)	100	101	101	100	101	101	100	101	100
Dimension 3 (mm)	100	100	100	100	99	100	100	100	100
Mass (kg)	2.351	2.375	2.359	2.375	2.355	2.378	2.366	2.371	2.37
Gauge Reading (kN)	401.4	414.7	409.5	523.1	499.8	535.8	541.2	560.7	571.9
Density (kg/m^3)	2351	2351	2336	2375	2309	2354	2366	2348	2370
Compressive Strength (Mpa)	40.14	41.47	40.95	52.31	49.98	53.58	54.12	56.07	57.19
Mean Compressive Strength (Mpa)	**40.9**			**52.0**			**55.8**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results acceptable

Laboratory Technician: Sabelo Zulu   Date: 16/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 40%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	23/09/2013			23/09/2013					
Test Date	23/03/2014			23/09/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	100	100			
Dimension 2 (mm)	100	100	99	100	99	99			
Dimension 3 (mm)	100	100	101	100	100	100			
Mass (kg)	2.374	2.356	2.352	2.344	2.353	2.348			
Gauge Reading (kN)	570.5	535	549.7	570.9	592	577.9			
Density (kg/m^3)	2374	2356	2352	2344	2377	2372			
Compressive Strength (Mpa)	57.05	53.50	54.97	57.09	59.20	57.79			
Mean Compressive Strength (Mpa)	**55.2**			**58.0**					
Comments	Cured in water			Cured in water					

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu Date: 23/09/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 50%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	04/10/2013			04/10/2013			04/10/2013		
Test Date	05/10/2013			11/10/2013			18/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			35		
Dimension 1 (mm)	100	99	100	100	100	100	100	100	100
Dimension 2 (mm)	100	98	100	99	100	100	99	100	99
Dimension 3 (mm)	98	99	100	100	100	100	100	100	100
Mass (kg)	2.24	2.184	2.254	2.261	2.268	2.269	2.265	2.286	2.261
Gauge Reading (kN)	13	13.9	12.5	128.8	123.1	135.6	247.5	251.4	260.3
Density (kg/m^3)	2286	2274	2254	2284	2268	2269	2288	2286	2284
Compressive Strength (Mpa)	1.30	1.39	1.25	12.88	12.31	13.56	24.75	25.14	26.03
Mean Compressive Strength (Mpa)	**1.3**			**12.9**			**25.3**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

Laboratory Technician: Sabelo Zulu Date: 18/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 50%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	04/10/2013			04/10/2013			04/10/2013		
Test Date	01/11/2013			29/11/2013			27/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	100	100	101	100	100	100
Dimension 2 (mm)	99	100	98	98	99	100	99	99	98
Dimension 3 (mm)	100	100	101	100	100	100	100	100	100
Mass (kg)	2.28	2.285	2.26	2.256	2.263	2.502	2.286	2.291	2.276
Gauge Reading (kN)	360	350.6	360.3	449.2	484.7	447.7	498	497.3	474.8
Density (kg/m^3)	2303	2285	2283	2302	2286	2477	2309	2314	2322
Compressive Strength (Mpa)	36.00	35.06	36.03	44.92	48.47	44.77	49.80	49.73	47.48
Mean Compressive Strength (Mpa)	**35.7**			**46.1**			**49.0**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results acceptable

Laboratory Technician: Sabelo Zulu Date: 27/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 50%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	04/10/2013			04/10/2013					
Test Date	02/04/2014			04/10/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	100	100			
Dimension 2 (mm)	100	99	99	98	99	99			
Dimension 3 (mm)	100	100	100	100	100	100			
Mass (kg)	2.301	2.281	2.276	2.269	2.262	2.278			
Gauge Reading (kN)	490.2	493.5	494.5	533	536.1	531.1			
Density (kg/m^3)	2301	2304	2299	2315	2285	2301			
Compressive Strength (Mpa)	49.02	49.35	49.45	53.30	53.61	53.11			
Mean Compressive Strength (Mpa)	**49.3**			**53.3**					
Comments	Cured in water			Cured in water					

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu Date: 04/10/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 60%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	10/10/2013			10/10/2013			10/10/2013		
Test Date	11/10/2013			17/10/2013			24/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	98	101	100	102	100	100
Dimension 2 (mm)	99	99	99	99	99	98	98	100	99
Dimension 3 (mm)	100	100	100	102	99	100	99	100	100
Mass (kg)	2.274	2.283	2.27	2.301	2.257	2.251	2.264	2.284	2.275
Gauge Reading (kN)	47.8	46	45	135.8	145	135.6	207.1	204.1	214.4
Density (kg/m^3)	2297	2306	2293	2325	2280	2297	2288	2284	2298
Compressive Strength (Mpa)	4.78	4.60	4.50	13.58	14.50	13.56	20.71	20.41	21.44
Mean Compressive Strength (Mpa)	**4.6**			**13.9**			**20.9**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

Laboratory Technician: Sabelo Zulu Date: 24/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 60%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	10/10/2013			10/10/2013			10/10/2013		
Test Date	07/11/2013			05/12/2013			02/01/2014		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	35			-			-		
Dimension 1 (mm)	100	100	101	100	100	100	100	100	100
Dimension 2 (mm)	98	98	99	99	99	99	98	99	98
Dimension 3 (mm)	100	100	99	101	101	100	100	100	100
Mass (kg)	2.264	2.277	2.261	2.289	2.314	2.29	2.292	2.289	2.28
Gauge Reading (kN)	342	354.9	338.6	426.9	422.9	439.9	431.4	428.9	441.8
Density (kg/m^3)	2310	2323	2284	2289	2314	2313	2339	2312	2327
Compressive Strength (Mpa)	34.20	35.49	33.86	42.69	42.29	43.99	43.14	42.89	44.18
Mean Compressive Strength (Mpa)	**34.5**			**43.0**			**43.4**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results conditionally acceptable

Laboratory Technician: Sabelo Zulu Date: 02/01/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	35MPa/9,5 - 60%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	10/10/2013			10/10/2013					
Test Date	08/04/2014			10/10/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	100	100			
Dimension 2 (mm)	100	99	99	99	98	100			
Dimension 3 (mm)	100	100	100	100	100	100			
Mass (kg)	2.32	2.304	2.272	2.297	2.296	2.323			
Gauge Reading (kN)	471.5	490.2	462.3	526.7	523.5	501.7			
Density (kg/m^3)	2320	2327	2295	2320	2343	2323			
Compressive Strength (Mpa)	47.15	49.02	46.23	52.67	52.35	50.17			
Mean Compressive Strength (Mpa)	**47.5**			**51.7**					
Comments	Cured in water			Cured in water					

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu   Date: 10/10/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 30%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	18/09/2013			18/09/2013			18/09/2013		
Test Date	20/09/2013			26/09/2013			02/10/2013		
Age of Specimen (days)	2	2	2	8	8	8	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	100	100	100	101	101	100	102	98	100
Dimension 3 (mm)	101	101	99	101	100	100	100	100	100
Mass (kg)	2.349	2.367	2.3	2.422	2.388	2.395	2.408	2.322	2.377
Gauge Reading (kN)	105	109	107	388.8	396	381.6	498	450.4	450.7
Density (kg/m^3)	2326	2344	2323	2374	2364	2395	2361	2369	2377
Compressive Strength (Mpa)	10.50	10.90	10.70	38.88	39.60	38.16	49.80	45.04	45.07
Mean Compressive Strength (Mpa)	**10.7**			**38.9**			**46.6**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

Laboratory Technician: Sabelo Zulu   Date: 02/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 30%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	18/09/2013			18/09/2013			18/09/2013		
Test Date	16/10/2013			13/11/2013			11/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	50			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	101	100	102	100	100	101	101	100	100
Dimension 3 (mm)	100	100	101	100	100	100	100	101	100
Mass (kg)	2.384	2.33	2.416	2.419	2.374	2.418	2.378	2.415	2.373
Gauge Reading (kN)	614.2	669.4	639.6	768.3	723.3	766	775.5	807	787.3
Density (kg/m^3)	2360	2330	2345	2419	2374	2394	2354	2391	2373
Compressive Strength (Mpa)	61.42	66.94	63.96	76.83	72.33	76.60	77.55	80.70	78.73
Mean Compressive Strength (Mpa)	**64.1**			**75.3**			**79.0**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu Date: 11/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 30%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	18/09/2013			18/09/2013					
Test Date	17/04/2014			18/09/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	101	100	100	100	101			
Dimension 2 (mm)	101	101	100	100	102	101			
Dimension 3 (mm)	100	100	100	100	100	100			
Mass (kg)	2.454	2.432	2.399	2.413	2.431	2.416			
Gauge Reading (kN)	840.9	814.6	825.6	833.1	844.9	833.9			
Density (kg/m^3)	2430	2384	2399	2413	2383	2368			
Compressive Strength (Mpa)	84.09	81.46	82.56	83.31	84.49	83.39			
Mean Compressive Strength (Mpa)	**82.7**			**83.7**					
Comments	Cured in water			Cured in water					

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu Date: 18/09/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 40%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	01/10/2013			01/10/2013			01/10/2013		
Test Date	02/10/2013			08/10/2013			15/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	101	100	100	100	100	102	101	100	101
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.265	2.258	2.275	2.274	2.27	2.311	2.279	2.259	2.294
Gauge Reading (kN)	36	35	40	243.3	231.7	245.9	365.8	378.9	399.8
Density (kg/m^3)	2243	2258	2275	2274	2270	2266	2256	2259	2271
Compressive Strength (Mpa)	3.60	3.50	4.00	24.33	23.17	24.59	36.58	37.89	39.98
Mean Compressive Strength (Mpa)	**3.7**			**24.0**			**38.2**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: Cube results have failed to meet the required strength at 28 days.
The concrete mix design needs to be ammended

Laboratory Technician: Sabelo Zulu Date: 15/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 40%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	01/10/2013			01/10/2013			01/10/2013		
Test Date	29/10/2013			26/11/2013			24/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	50			-			-		
Dimension 1 (mm)	100	100	99	100	100	100	100	100	100
Dimension 2 (mm)	100	102	101	101	100	101	101	100	102
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.253	2.295	2.28	2.288	2.275	2.287	2.324	2.309	2.315
Gauge Reading (kN)	469.7	477.4	493.5	575.3	610.8	604.6	636.6	678.3	639.8
Density (kg/m^3)	2253	2250	2280	2265	2275	2264	2301	2309	2270
Compressive Strength (Mpa)	46.97	47.74	49.35	57.53	61.08	60.46	63.66	67.83	63.98
Mean Compressive Strength (Mpa)	**48.0**			**59.7**			**65.2**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results conditionally acceptable

Laboratory Technician: Sabelo Zulu   Date: 24/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 40%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	01/10/2013			01/10/2013					
Test Date	30/03/2014			01/10/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	100	100	100	100			
Dimension 2 (mm)	101	101	101	100	101	102			
Dimension 3 (mm)	100	100	101	100	100	100			
Mass (kg)	2.301	2.308	2.335	2.299	2.316	2.315			
Gauge Reading (kN)	635.1	658	676.7	670.9	707.9	641.1			
Density (kg/m^3)	2278	2285	2289	2299	2293	2270			
Compressive Strength (Mpa)	63.51	65.80	67.67	67.09	70.79	64.11			
Mean Compressive Strength (Mpa)	**65.7**			**67.3**					
Comments	Cured in water			Cured in water					

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu Date: 01/10/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 50%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	07/10/2013			07/10/2013			07/10/2013		
Test Date	08/10/2013			14/10/2013			21/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	98	99	99	98	99	100	98	99	99
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.218	2.23	2.22	2.231	2.258	2.25	2.231	2.244	2.276
Gauge Reading (kN)	15	15	13	231.5	208.1	205.2	304.3	341.2	340.2
Density (kg/m^3)	2263	2253	2242	2277	2281	2250	2277	2267	2299
Compressive Strength (Mpa)	1.50	1.50	1.30	23.15	20.81	20.52	30.43	34.12	34.02
Mean Compressive Strength (Mpa)	**1.4**			**21.5**			**32.9**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

Laboratory Technician: Sabelo Zulu Date: 21/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 50%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	07/10/2013			07/10/2013			07/10/2013		
Test Date	04/11/2013			02/12/2013			30/12/2013		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	50			-			-		
Dimension 1 (mm)	100	100	101	100	100	100	100	102	100
Dimension 2 (mm)	98	98	100	100	98	99	99	98	99
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.248	2.266	2.26	2.27	2.221	2.255	2.284	2.274	2.245
Gauge Reading (kN)	525.3	543.7	509.8	616.2	614.7	654.2	648	638.7	644
Density (kg/m^3)	2294	2312	2238	2270	2266	2278	2307	2275	2268
Compressive Strength (Mpa)	52.53	54.37	50.98	61.62	61.47	65.42	64.80	63.87	64.40
Mean Compressive Strength (Mpa)	**52.6**			**62.8**			**64.36**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu   Date: 30/12/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 50%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	07/10/2013			07/10/2013					
Test Date	05/04/2014			07/10/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	100	100	101	98	100	100			
Dimension 2 (mm)	98	99	100	100	98	99			
Dimension 3 (mm)	100	100	99	101	101	100			
Mass (kg)	2.244	2.279	2.233	2.272	2.256	2.267			
Gauge Reading (kN)	667.7	678	619.3	670.9	635.6	673.4			
Density (kg/m^3)	2290	2302	2233	2295	2279	2290			
Compressive Strength (Mpa)	66.77	67.80	61.93	67.09	63.56	67.34			
Mean Compressive Strength (Mpa)	**65.5**			**66.0**					
Comments	Cured in water			Cured in water					

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu Date: 07/10/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 60%FA

Specimen Number	001	002	003	004	005	006	007	008	009
Cast Date	11/10/2013			11/10/2013			11/10/2013		
Test Date	12/10/2013			18/10/2013			25/10/2013		
Age of Specimen (days)	1	1	1	7	7	7	14	14	14
Specified Strength (Mpa)	-			-			-		
Dimension 1 (mm)	100	100	100	100	100	100	100	100	100
Dimension 2 (mm)	100	100	99	100	100	99	100	101	100
Dimension 3 (mm)	100	100	100	100	100	100	100	100	100
Mass (kg)	2.26	2.256	2.261	2.269	2.269	2.266	2.277	2.293	2.295
Gauge Reading (kN)	62	69.1	62.4	254.8	251.9	246.3	371.5	357.7	377.9
Density (kg/m^3)	2260	2256	2284	2269	2269	2289	2277	2270	2295
Compressive Strength (Mpa)	6.20	6.91	6.24	25.48	25.19	24.63	37.15	35.77	37.79
Mean Compressive Strength (Mpa)	**6.5**			**25.1**			**36.9**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: ....

Laboratory Technician: Sabelo Zulu Date: 25/10/2013

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 60%FA

Specimen Number	010	011	012	013	014	015	016	017	018
Cast Date	11/10/2013			11/10/2013			11/10/2013		
Test Date	08/11/2013			06/12/2013			03/01/2014		
Age of Specimen (days)	28	28	28	56	56	56	84	84	84
Specified Strength (Mpa)	50			-			-		
Dimension 1 (mm)	100	100	100	100	100	99	101	102	100
Dimension 2 (mm)	99	98	98	100	100	100	100	100	101
Dimension 3 (mm)	100	100	100	100	100	100	100	99	100
Mass (kg)	2.277	2.254	2.263	2.296	2.261	2.271	2.308	2.314	2.268
Gauge Reading (kN)	530.2	545	520.5	594.3	600.6	611.8	616.4	602.5	597.6
Density (kg/m^3)	2300	2300	2309	2296	2261	2294	2285	2292	2246
Compressive Strength (Mpa)	53.02	54.50	52.05	59.43	60.06	61.18	61.64	60.25	59.76
Mean Compressive Strength (Mpa)	**53.2**			**60.2**			**60.6**		
Comments	Cured in water			Cured in water			Cured in water		

Remarks: 28 day results accepted

Laboratory Technician: Sabelo Zulu Date: 03/01/2014

CONCRETE CUBE TEST REPORT

Project	Dissertation: Optimization of Fly Ash use in Concrete
Structure	Test Concrete Mixtures
Mix Description	50MPa/9,5 - 60%FA

Specimen Number	019	020	021	022	023	024			
Cast Date	11/10/2013			11/10/2013					
Test Date	09/04/2014			11/10/2014					
Age of Specimen (days)	180	180	180	365	365	365			
Specified Strength (Mpa)	-			-					
Dimension 1 (mm)	99	100	101	101	100	100			
Dimension 2 (mm)	100	99	100	99	100	100			
Dimension 3 (mm)	100	100	100	100	100	100			
Mass (kg)	2.271	2.267	2.3	2.31	2.294	2.276			
Gauge Reading (kN)	647.6	647.2	602	649.7	659	681.1			
Density (kg/m^3)	2294	2290	2277	2310	2294	2276			
Compressive Strength (Mpa)	64.76	64.72	60.20	64.97	65.90	68.11			
Mean Compressive Strength (Mpa)	**63.2**			**66.3**					
Comments	Cured in water			Cured in water					

Remarks: results acceptable

Laboratory Technician: Sabelo Zulu Date: 11/10/2014

Appendix F: Plastic Properties of 35 MPa Concrete Mixes

Client : Sabelo Zulu   Lab Ref. : CS14/09/1144

Project : M- Tech Research

Client Mix Ref.		35MPa/30	35MPa/40	35MPa/50	35MPa/60	35MPa/0
Contest Mix Ref.		CT1032	CT1039	CT1048	CT1054	CT1148
Material	Units	Quanity (kg/m3)				
Cement (OPC 52.5N CEM I)	kg	5,32	4,56	3,8	3,04	7,6
River Sand	kg	17,2	17,2	17,2	17,2	17,2
Fly Ash	kg	2,28	3,04	3,8	4,56	0
9.5mm Stone	kg	17,0	17,0	17,0	17,0	17,0
Water	L	4,5	4,5	4,5	4,5	4,5
Slump	mm	70	85	85	75	55
Air Content (%)	-	2,1	2,2	2,0	1,3	0,5
Initial Setting (minutes)	hours & minutes	8hrs & 40min		10hrs & 40min	11hrs & 24min	7hrs
Final Setting (minutes)	hours & minutes	12hrs & 24min	13hrs & 47min	13hrs & 28min	14hrs & 38min	8hrs & 45 min

Appendix G: Drying Shrinkage of 35 MPa Concrete Mixes

CONTEST
Concrete Technology Services
P O Box 1675, Hillcrest, 3650, South Africa. Tel (031) 700 9394 (031) 700 9342
E-mail : contest@contest.co.za, Web Page: www.contest.co.za

Ref: CS14/09/1144 19 November 2014

Client: Sabelo Zulu

Project:

Subject: SABS 1085 Shrinkage

LABORATORY REPORT
SHRINKAGE TESTING OF CONCRETE
SABS 1085:1994

CLIENT

Sabelo Zulu

SYNOPSIS

Initial drying shrinkage tests were carried out on four samples of concrete manufactured by Contest laboratory.

The average shrinkage of the specimens has been provided.

BRIEF

Contest carried out initial drying shrinkage tests in accordance with SABS Method 1085:1994 on four samples of concrete in Contest's laboratory.

TESTING

Contest manufactured 100x100x300 mm shrinkage specimens.

Initial drying shrinkage tests were carried out essentially in accordance with SABS Method 1085:1994.

Initial drying shrinkage (SABS STM 1085)

Reference	Initial shrinkage (%)			Average Shrinkage (%)
CT1032	0.046	0.046	0.044	0.05

Adam Investments cc. Reg. No 1988/019362/23 t/a CONTEST Concrete Technology Services
Managing Member: RJL Raw B Tech (Civil Eng)
Members: MT Clark, JS Dunnett, MC Mzobe, VA Horton
Consultant: A J M Horton Pr Tech (Eng), Dip ACT, HND (Chem), HNC (Civ. Eng),FICT, MSA Corr I

Testing, Training and Consulting in Concrete

Ref: CS14/09/1144 19 November 2014

Client: Sabelo Zulu

Project:

Subject: SABS 1085 Shrinkage

Reference	Initial shrinkage (%)			Average Shrinkage (%)
CT1039	0.051	0.048	0.047	0.05

Reference	Initial shrinkage (%)			Average Shrinkage (%)
CT1048	0.054	0.055	0.054	0.05

Reference	Initial shrinkage (%)			Average Shrinkage (%)
CT1054	0.054	0.057	0.056	0.06

COMMENT:

The following is an extract from the Cement and Concrete Institute's Commentary to SABS 1083:1994, which may be used for interpreting the results for Shrinkage;

No acceptance limits have been set for results obtained by this test. Analysis of a limited number of results shows that most results fall within the range 0.02% to 0.065%. These results included mixes using a variety of binder types and some chemical admixtures. The mean value was approximately 0.045%. Results for plain OPC mixes covered a similar range (0.02% to 0.065%) but the mean value was approximately 0.04%.

R J L Raw
B Tech (Civil Eng)

Appendix H: 7-Days Durability Testing Report

CONTEST

Concrete Technology Services

P O Box 1675, Hillcrest, 3650, South Africa. Tel (031) 700 9394 (031) 700 9342
E-mail : contest@contest.co.za Web Page: www.contest.co.za

Ref: CS13/09/933 2 October 2013

Client: Sabelo Zulu

Project: None given

Subject: Durability Index Testing – 7d

O/N: Sabelo

DURABILITY TESTING

CLIENT

Sabelo Zulu

CLIENTS BRIEF

Contest were requested to carry out the necessary slicing, conditioning and testing of cores to determine Oxygen Permeability, Water Sorptivity and Chloride Conductivity.

SAMPLES

Sixteen concrete cores were drilled from cubes manufactured by the client and tested on 28.09.2013 referenced as follows;

Quantity	Specimen Reference	Date Cast
4	Mix 35/30	13.09.2013
4	Mix 35/40	13.09.2013
4	Mix 35/50	13.09.2013
4	Mix 35/60	13.09.2013

PREPARATION

The cores listed above were sliced and conditioned in accordance with the latest procedures issued in the draft SABS standard.

TESTING

The slices were then tested using the described procedures for Oxygen Permeability (OPI), Water Sorptivity (WS) and Chloride Conductivity using the necessary equipment and apparatus.

Adam Investments cc. Reg. No 1988/019362/23 t/a CONTEST Concrete Technology Services
Managing Member: RJL Raw B Tech (Civil Eng)
Members: MT Clark, JS Dunnett, MC Mzobe, VA Horton
Consultant: A J M Horton Pr Tech (Eng), Dip ACT, HND (Chem), HNC (Civ. Eng),FICT, MSA Corr I

Ref:	CS13/09/933	2 October 2013
Client:	Sabelo Zulu	
Project:	None given	
Subject:	Durability Index Testing – 7d	
O/N:	Sabelo	

TEST RESULTS

The following results were obtained from tests carried out on 26.09.2013.

Mix 35/30

Oxygen Permeability (log value)		
Sample	A	9.92
	B	9.60
	C	9.50
	D	9.85
AVERAGE		**9.68**
CoV		**45.29**
Water Sorptivity (mm/√hr)		
Sample	A	10.63
	B	11.99
	C	13.04
	D	10.39
AVERAGE		**11.51**
CoV		**10.75**
Chlorides (mS/cm)		
Sample	A	2.20
	B	2.14
	C	2.26
	D	2.23
AVERAGE		**2.21**
CoV		**2.4**

Mix 35/40

Oxygen Permeability (log value)		
Sample	A	9.70
	B	9.35
	C	9.65
	D	9.61
AVERAGE		**9.56**
CoV		**40.19**
Water Sorptivity (mm/√hr)		
Sample	A	13.33
	B	13.45
	C	13.65
	D	14.21
AVERAGE		**13.66**
CoV		**2.84**
Chlorides (mS/cm)		
Sample	A	2.17
	B	2.00
	C	1.97
	D	2.00
AVERAGE		**2.03**
CoV		**4.4**

Ref:	CS13/09/933	2 October 2013
Client:	Sabelo Zulu	
Project:	None given	
Subject:	Durability Index Testing – 7d	
O/N:	Sabelo	

Mix 35/50

Oxygen Permeability (log value)		
Sample	A	9.46
	B	9.34
	C	9.42
	D	9.35
AVERAGE		**9.39**
CoV		**12.91**
Water Sorptivity (mm/√hr)		
Sample	A	14.15
	B	15.12
	C	14.56
	D	15.63
AVERAGE		**14.86**
CoV		**4.34**
Chlorides (mS/cm)		
Sample	A	2.07
	B	2.25
	C	2.03
	D	2.10
AVERAGE		**2.11**
CoV		**4.5**

Mix 35/60

Oxygen Permeability (log value)		
Sample	A	9.21
	B	9.03
	C	9.19
	D	9.04
AVERAGE		**9.11**
CoV		**21.96**
Water Sorptivity (mm/√hr)		
Sample	A	18.84
	B	17.37
	C	20.60
	D	13.67
AVERAGE		**17.62**
CoV		**16.71**
Chlorides (mS/cm)		
Sample	A	2.65
	B	2.77
	C	3.00
	D	2.71
AVERAGE		**2.78**
CoV		**5.5**

COMMENT

The specification requirements were not supplied to Contest and therefore no comment can be made in this regard.

[redacted]

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B Tech (Civil Eng)

Appendix I: 28-Days Durability Testing Report

CONTEST
Concrete Technology Services

P O Box 1675, Hillcrest, 3650, South Africa. Tel (031) 700 9394 (031) 700 9342
E-mail : contest@contest.co.za Web Page: www.contest.co.za

Ref: CS13/09/933 22 October 2013

Client: Sabelo Zulu

Project: None given

Subject: Durability Index Testing – 28d

O/N: Sabelo

DURABILITY TESTING

CLIENT

Sabelo Zulu

CLIENTS BRIEF

Contest were requested to carry out the necessary slicing, conditioning and testing of cores to determine Oxygen Permeability, Water Sorptivity and Chloride Conductivity.

SAMPLES

Sixteen concrete cores were drilled from cubes manufactured by the client and tested on 18.10.2013 referenced as follows;

Quantity	Specimen Reference	Date Cast
4	Mix 35/30	13.09.2013
4	Mix 35/40	13.09.2013
4	Mix 35/50	13.09.2013
4	Mix 35/60	13.09.2013

PREPARATION

The cores listed above were sliced and conditioned in accordance with the latest procedures issued in the draft SABS standard.

TESTING

The slices were then tested using the described procedures for Oxygen Permeability (OPI), Water Sorptivity (WS) and Chloride Conductivity using the necessary equipment and apparatus.

Ref:	CS13/09/933
Client:	Sabelo Zulu
Project:	None given
Subject:	Durability Index Testing – 28d
O/N:	Sabelo

22 October 2013

TEST RESULTS

The following results were obtained from tests carried out on 18.10.2013.

Mix 35/30

Oxygen Permeability (log value)		
Sample	A	9.54
	B	10.32
	C	10.08
	D	10.08
AVERAGE		**9.90**
CoV		**88.17**
Water Sorptivity (mm/√hr)		
Sample	A	10.27
	B	9.27
	C	9.53
	D	9.64
AVERAGE		**9.68**
CoV		**4.38**
Chlorides (mS/cm)		
Sample	A	1.59
	B	1.53
	C	1.65
	D	1.66
AVERAGE		**1.61**
CoV		**3.8**

Mix 35/40

Oxygen Permeability (log value)		
Sample	A	10.16
	B	10.21
	C	10.02
	D	10.02
AVERAGE		**10.09**
CoV		**21.59**
Water Sorptivity (mm/√hr)		
Sample	A	8.50
	B	9.26
	C	10.18
	D	13.25
AVERAGE		**10.30**
CoV		
Chlorides (mS/cm)		
Sample	A	1.73
	B	1.65
	C	1.64
	D	1.77
AVERAGE		**1.70**
CoV		**3.6**

Ref: CS13/09/933 22 October 2013

Client: Sabelo Zulu

Project: None given

Subject: Durability Index Testing – 28d

O/N: Sabelo

Mix 35/50

Oxygen Permeability (log value)		
Sample	A	10.01
	B	10.07
	C	9.82
	D	9.79
AVERAGE		**9.91**
CoV		**30.88**
Water Sorptivity (mm/√hr)		
Sample	A	9.42
	B	11.22
	C	9.60
	D	10.47
AVERAGE		**10.18**
CoV		**8.20**
Chlorides (mS/cm)		
Sample	A	1.25
	B	1.16
	C	1.29
	D	1.30
AVERAGE		**1.25**
CoV		**5.0**

Mix 35/60

Oxygen Permeability (log value)		
Sample	A	9.94
	B	9.88
	C	9.89
	D	9.66
AVERAGE		**9.83**
CoV		**32.38**
Water Sorptivity (mm/√hr)		
Sample	A	9.39
	B	11.09
	C	10.83
	D	10.95
AVERAGE		**10.56**
CoV		**7.46**
Chlorides (mS/cm)		
Sample	A	1.29
	B	1.46
	C	1.29
	D	1.35
AVERAGE		**1.35**
CoV		**5.9**

Ref:	CS13/09/933	22 October 2013
Client:	Sabelo Zulu	
Project:	None given	
Subject:	Durability Index Testing – 28d	
O/N:	Sabelo	

COMMENT

The specification requirements were not supplied to Contest and therefore no comment can be made in this regard.

[redacted]

R J L Raw
B Tech (Civil Eng)

AUTHOR'S RESUME

CONTACT DETAILS:

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EDUCATION:

Durban University of Technology (DUT)

- Master of Engineering: Civil 2013 to 2016
- B-Tech: Civil Engineering, Structures 2008
- National Diploma: Civil Engineering 2004

WORK EXPERIENCE:

Engineer Representative - Royal Haskoning DHV/ SSI 2005 to date

- Construction of 9,3Ml Reinforced Concrete Reservoir, Durban 2016 to 2017
- Macambini Water Supply Scheme 2016 to 2017
- Construction of 23km Welded Steel Pipeline, Durban 2014 to 2016
- Construction of 5Ml Reinforced Concrete Reservoir, Mandeni 2013 to 2014
- Construction of 10Ml Reinforced Concrete Reservoir, Mandeni 2012 to 2013
- Construction of 13Ml/day Extension to Sundumbili Waterworks, Mandeni 2010 to 2012
- Construction of 5Ml Reinforced Concrete Reservoir, Durban 2010
- Construction of 1400 ND & 1600 ND Steel Pipeline, Durban 2010
- Installation of Mechanical Grit Separation and Screening equipment, Durban 2010
- Installation of odor control equipment, Durban 2009
- Rehabilitation of beaches and facilities, Margate 2009
- Rehabilitation of beaches and facilities, Scottburgh 2008
- Construction of 15Ml Reinforced Concrete Reservoirs, Amanzimtoti 2006 to 2008
- Rehabilitation of Shallcross sewer reticulation, Durban 2008
- Construction of 10Ml Reinforced Concrete Reservoir, Mandeni 2005 to 2006
- Construction of 600 ND & 700 ND Steel Pipeline, Mandeni 2005 to 2006

Technician – Biggar Joubert consulting 2003 - 2005

- Structural design, detailing and draughting 2005
- Construction supervision- Welbedacht Trunk sewer construction, Durban 2003
- Water Loss Management, eThekwini Municipality 2003

Technical Assistant – Lescon Civils 2002

- Construction of Old Fort Road Parkings, Durban 2002

OTHER EXPERIENCE:

- EGD Teacher – Royal Haskoning DHV Saturday School Initiative 2010 to date
- Drawing Tutor – Durban University of Technology 2004

PUBLICATIONS AND PAPERS:

- The Cement Business and Industry Africa Conference 2016 (Guest Speaker): *Evaluating the effects of utilizing high fly-ash content in concrete* - 2016.
- International Journal of Engineering Sciences Research and Technology (IJESRT): *Effects and benefits of using high content of FA in concrete* - 2016.
- 34th Annual Southern African Transport Conference and Exhibition: *Optimizing the usage of FA in concrete in the construction of roadworks – 2015.*
- International Journal of Engineering and Innovative Technology (IJEIT): *Influence of high content FA on concrete durability*- 2014.
- 8th Built Environment Conference ASOSCA: *Optimizing the usage of FA in concrete* – 2014.
- DUT Institutional Research Day: *Optimizing the use of FA in roads construction* – 2013.

PROFESSIONAL MEMBERSHIPS:

- ECSA – Candidate Technologist
- CSSA - Member
- SAICE - Member