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Suleman, Riaz

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Performance of Selected South African Cements Based on Solar Chamber, Pycnometer, Chemical and Physical Tests

A Research Report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the Requirements for the degree of Master of Science in Engineering.

R. Suleman

Johannesburg, 2014

Declaration

This research report is submitted to the Faculty of Engineering and the Built Environment of the University of the Witwatersrand in partial fulfilment of the requirements for the degree of Master of Science in Engineering. It has not been submitted before for any degree or examination at any other institution. Sources of acknowledgement and references have been provided.

Signed: _____

R. Suleman

September 2014

Abstract

The performance of cement in concrete can be argued to include strength, durability, economy, aesthetics as well as workability. In this research report, various local South African cements as well as a cement from Germany and Pakistan have been studied for various aspects such as strength, durability and hydration characteristics. Three curing regimes have been investigated. The curing regimes included curing in water, air and in a solar chamber to determine the strength and durability performance of the cements under study. The chemical performance of certain cements has been assessed in terms of sulphur, chloride and insoluble residue contents. Pycnometers have been utilised to determine whether the hydration characteristics can be followed for different grades of cements and mixes containing fly ash. X-ray fluorescence studies on hardened mortar have also been investigated on the mortar mixes from the pycnometer study in order to assess whether the technique may be useful to assess the hydration characteristics of the various mixes. On the whole, the strength and durability results show the importance of moisture in curing even though discrepancies were encountered. The chemical performance of the cements were found to perform satisfactorily with respect to standard codes of practice. The pycnometers may be a useful technique to assess the hydration of various mixes but require careful procedural processes. The x-ray fluorescence portion of the study revealed that the technique is not useful to assess the hydration characteristics of mortar over time.

Key words: Cement, concrete, hydration, solar chamber, pycnometer, strength, durability.

Dedication

To all my awesome teachers and lecturers over the years, my friends, my very kind hearted and affectionate sisters, my special mum and dad. Thank you everybody for all your motivation, support, time, patience, prayers and good wishes – May the Creator always bless all of you with good fortune and many blessings, amen.

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List of Cements in Study

Code	Notation
A1	CEM IV/B-V 32,5N
A2	CEM IV/B-V 32,5R
B	CEM V/A (S-V) 32.5N
C	CEM III A 32.5N

List of 32.5 Cements

Code	Notation
D1	CEM II/A-M (V-L) 42,5N
D2	CEM II A-M (V-L) 42.5R
E	CEM II B/M (S-V) 42.5N
F1	CEM I 42.5N (Pakistan)
F2	CEM I 42.5R (Germany)
G	CEM II A-L 42.5N

List of 42.5 Cements

Code	Notation
H1	CEM I 52.5N
H2	CEM I 52.5R
I	CEM II/A-V 52,5N

List of 52.5 Cements

1. Chapter One: Introduction

1.1. Cement Industry in South Africa

Cement is one of the principle materials used in the construction industry and can be argued to be important for the development of modern society (Arikan, 2004).

Cement manufacture in South Africa begun as early as 1892 with the first cement manufacturing plant opened in the Daspoort area of Pretoria (Ofori, et al., 1996). On a global scale, cement production in Africa was estimated at approximately 4.5% of the total cement production in the world in 2012 (CEMBUREAU, 2012).

The South African concrete industry is a coordinated sector involving a wide range of key members ranging from the cement manufacturers to the simple artisans and as Ballim and Ekolu (2006) go on to further mention, it is an organised industry unlike in many parts of Africa. However, the cement industry does have its own challenges. Some of the issues that have faced the industry include poor durability of concrete and supervision (Rwelamila & Wiseman, 1995).

There are four major cement manufacturers in South Africa. Heyns (2013) mentions them as Afrisam, Lafarge, Pretoria Portland Cement (PPC) and Natal Portland Cement (NPC). Besides these companies there are third party blenders which operate in different parts of the country. Third party blenders operate by purchasing cementitious materials from the main stream market, blend their own mixes and package the finished products in their own packaging (Poggiolini, 2012).

Cement consumption in South Africa was approximately 15.5 million tonnes per annum in 2007 (Heyns, 2013).

Imported cement, believed to be significantly noticeable with approximately five to seven percent accounting for the total consumption (Global Cement (a), 2013; Global Cement (b), 2013). In 2011, sales were halted on an imported brand of cement from Pakistan as there was concern over the quality and standard of the cement brand known as Lucky cement (Global Cement, 2012).

Cement is an important material for the construction industry. South Africa being a developing country has experienced good trends in building and construction. Following this trend, there is a new company, Sephaku, that will operate amongst the four major

manufacturers in South Africa and is the first company to invest in the cement manufacturing field since 1934 (Heyns, 2013). Sephaku expects to produce 2.6 million tonnes per annum (Heyns, 2013).This may be testament to the potential for cement demand and growth in the construction industry in the years to come.

Cement manufacturers are compelled to comply with South African National Standards. The various cement products are accredited usually by the South African National Bureau of Standards (SABS). However, despite the fact that cement manufacturers are signatories to external supervision, it would add value for an independent institution to investigate the performance of local cements. The findings would complement the reputation of the industry. Furthermore, the findings would allow for the manufacturers to consider the outcomes of the tests investigated from a different perspective whereby an independent institution critiques their cement products.

This research project details the results of an experimental study that investigated a wide range of cement properties. The tests were aimed at assessing the performance of various cements through chemical and physical tests. A Pakistani cement as well as a German cement were also investigated. These two imported brands of cement may provide for interesting discussion in comparing local cements with imported cements

1.2. Overview of the Tests Conducted in the Study

A wide range of physical and chemical tests were conducted which are described hereunder:

Several chemical tests were conducted in order to assess the chemical makeup of the cements. The chemical tests included determining the sulphate, insoluble residue and chloride contents.

Amongst the physical tests that were conducted, characterising the cement strengths, setting times, loss on ignition as well as specific surface areas were conducted.

The concrete making properties of the cements were investigated whereby the performance of the cements were characterised in terms of compressive strength and durability performance. This portion of the study involved investigating three types of curing regimes, namely, curing in air, water and in a solar chamber.

The final portion of the study involved investigating several fly ash blends. The fly ash blends were investigated for water absorption traits and elemental chemical composition using x-ray fluorescence.

1.3. Motivation for the Study

The chemical and physical tests that formed part of the study have been conducted on standard reference cement from Germany, selected South African Cements and a cement from Pakistan. It was anticipated that the series of tests would give an indication of the performance of locally available cements. The ambition was to determine how well local cements performed in relation to a country considered to be advanced in the field of cement engineering (Germany). It was also desired to infer the quality of cement from a country considered to be a developing country (Pakistan). Further motivation for the different chemical and physical tests is provided below:

The insoluble residue content provides an indication of cement adulteration. Basically, this test can be used to infer whether a manufacturer has blended items other than what is usually required in cement manufacture. Dishonest manufacturers or blenders use materials such as rock flour to bulk up space in cement bags. Adulteration could have serious implication on the strength and durability of concrete (Jaturapitakkul, et al., 2000).

Chloride and sulphate contents are important to regulate as these chemicals have an effect on the durability of concrete. With regards to the chloride content, this chemical can contribute towards corrosion (Brouwers & Florea, 2012). With regards to sulphate contents, expansion cracking and deterioration can be associated with this chemical (Hossain & Lachemi, 2006).

With regards to the physical tests conducted, the cement characteristic setting times were determined, loss on ignition as well as specific surface areas.

Setting times are useful for an indication of the time available to work, place and compact fresh concrete (Eren & Marar, 2009).

The specific surface area of cement offers an indication of the reactivity of cement. This can in turn affect the rate of gain of strength development (Chen, et al., 2011).

Mortar prisms were prepared to determine the strength development from which tests were conducted after two, seven and twenty eight days in order to characterise the strength performance of the cements.

The performances of the cements for use in concrete applications investigated strength development and durability assessment for three different curing regimes. The reason for investigating strength is because it is an important criterion for design. Durability considerations are important for ensuring that the concrete can withstand the conditions it is designed for (Wasserman & Bentur, 2012).

The curing regimes selected in the study were: (a) curing in water, (b) curing in air indoors and (c) curing in a solar chamber. As has already been alluded to, it is important to ensure adequate curing for good strength and durability.

Considering the work of Uzoegbo (1997), the third type of curing regime, namely solar chamber curing could have potential applications in the manufacture of low cost building items such as tiles.

The concluding portion of the study, Pycnometric studies, encompassed determining water absorption characteristics of mortar pastes and whether x-ray fluorescence XRF could be used to infer the degree of hydration whereby the mortar mixes from the pycnometer study were investigated.

The water absorption of the fly ash mortar pastes was assessed in order to evaluate whether one could predict degree of hydration over time.

The XRF test was inspired from a study conducted by Sisomphon (2009). Sisomphon (2009) had made use of XRF on concrete specimens in order to estimate varying contents of blast furnace slag in hardened concrete. The elemental oxide contents were determined after 28 and 91 days of curing. Even though the purpose for conducting XRF tests was not related to the present study of following water absorption trends, the results from Sisomphon (2009) were considered to be interesting to pursue as is motivated hereunder:

The results of the oxides from Sisomphon (2009) appeared to suggest that the degree of hydration could be estimated from an XRF analysis. A sample of the findings as shown in Table 1.1 suggests that it might be possible to infer the degree of hydration simply through making use of XRF on hydrated specimens after different periods.

Oxide % in the 30% Slag Mix	28 Days After Hydration	91 Days After Hydration
CaO	55.33	55.82
SiO_2	23.3	22.93
Al_2O_3	7.57	6.58
SO_3	0.93	1.38

Table 1.31: Sample XRF Results from Sisomphon (2009: Table 2: 56)

The contents of Calcium oxide and Sulphur oxide showed an increase after 28 and 91 days of curing whereas the contents of Silica oxide (SiO_2) and Aluminium oxide (Al_2O_3) showed a decrease.

The above observations appeared to be peculiar. It was not clear why the oxide contents had changed. At the time when Sisomphons (2009) paper was studied, the main question posed was, 'why should the oxide contents change? Why should the chemical composition of the mixes change with time?' Colloquially speaking, 'What you put in should be what you get out.'

Nonetheless, it was decided that perhaps there were chemical and physical processes that may have occurred over the course of hydration that resulted in the observations made by Sisomphon (2009). The possible reasons that were thought of at the time of investigation to explain the results follow:

Typically during hydration, Calcium oxide is one of the products that result from hydration of tri-calcium silicate (C_3S) and di-calcium silicate (C_2S) minerals upon contact with water (Addis, 2008). This could be an explanation for the increase in calcium oxide observed by Sisomphon (2009).

The silicate minerals of C_3S and C_2S react with water to form CSH over time (Islam, 2005). This could explain the decreasing silica contents documented by Sisomphon (2009).

The aluminium oxide decreasing could be explained from the hydration of the aluminate phases such as tri-calcium aluminate and tri-calcium aluminate ferrite (Addis, 2008).

It was not clear whether Sisomphon (2009) may have erred in the analysis. The principle question was: "Why should the elemental composition of the samples change after time since what you put in, should be what you get out? Possible reasons for a change in composition could be if there was leaching or chemicals are added to the system?"

To probe into the matter further, it was decided to conduct XRF analysis on the mortar mixes in a dry state before mixing with water and compare these oxides after twenty eight days of hydration in order to assess whether the degree of hydration could truly be assessed through XRF.

1.4. Expected outcomes

The chemical and physical tests would offer an insight the performance of the South African cements compared to the German reference cement and the Pakistani imported cement.

The insoluble residue content would give an indication of whether the cements investigated may have been unscrupulously adulterated in any way. The chloride contents would be useful to infer the performance of the cements in corrosive environments and the sulphate content to infer durability in harsh environments where expansion and cracking of concrete can be a concern for instance.

Determining the cement strengths would allow for an assessment of the performance of the cements in terms of strength development. The setting times would give an indication on the time before the mix sets so that a workman has sufficient time to place, compact and finish concrete. The degree of fineness would be useful for an assessment of the potential reactivity of the cement.

The influence of the solar chamber in terms of strength development and durability would offer insight into the usefulness and effectiveness of harnessing solar power to hydrate cement.

The usefulness of monitoring water consumption by mortar pastes in the pycnometer study would give an indication of the possibility of using the apparatus to predict whether is it possible to determine the optimal percentages to which cement can be blended.

The XRF studies would indicate whether it is possible to infer the degree and extent of hydration and whether optimal blends can also be determined through using XRF.

1.5. General Limitations of the Study

The chemical tests were only conducted on a limited number of cements. The range of mixes was also limited. The mineralogy and geological source of the cement constituents were unknown. The types of activators and strength enhancers which the cement manufacturers may have employed were also unknown. The period of investigation was limited as well. The cements tested were only tested once and so, the results are not representative of the long term performance of the cements. The study is an experimental investigation of the performance of the cements and reviews a limited number of tests.

1.6. Summary of Aims and Objectives

It is now appropriate to formally state the aims and objectives of the study.

1. Chemical and Physical Tests on the cements: This will provide an indication of the performance of the locally available cements in the South African market to those cements abroad. In particular, the German cement will offer an insight into the performance of cement

from a company considered to be advanced in the field of cement engineering whereas the Pakistani cement will offer insight into the performance of cement from a country considered to be a developing country. The chemical tests included: Chloride, sulphate and insoluble residue contents. The physical tests included cement setting times, loss on ignition and specific surface areas.

2. Concrete performance: 100mm concrete cubes (cement, sand and stone) were prepared for this portion of the study in order to assess the performance of the cements in concrete. This portion of the study would give an indication of the cement performance in practical building and construction works where cement is blended with aggregate. Workability, strength and durability were the items investigated in this category.

3. Hydration study: In this portion of the study, the pycnometer and XRF tests are classified. The usefulness of using pycnometers to follow the degree of hydration for various fly mixes and the usefulness of XRF on hardened mortar specimens before and after hydration have been studied.

These tests could be argued to give an indication of the cement performance and quality of the cement manufactured. However, such a bold statement cannot go without mentioning that the purpose for which a particular cement is manufactured must be borne in mind. One cement may be useful for a certain application but unsuitable for another.

1.7. Organisation of Report

Chapter two presents a literature review on related items that pertain to the study. Chapter three encompasses the materials under investigation as well as the experimental procedures. Chapter four details the findings from the experiments together with a discussion. Chapter five outlines key findings from the study and recommendations for future work.

2. Chapter 2: Literature Review

The literature review is divided into five parts. Part one details general aspects pertaining to cement technology such as the production of cement, extenders involved in cement manufacture.

Part two pertains to aspects related to the chemical aspects of the study and includes notes on insoluble residue, chloride and the sulphate tests as well as notes on the role of alkalis, magnesium in cements.

Part three presents literature related to physical aspects of tests conducted in the study such as setting time, loss on ignition and specific surface area tests.

Part four presents literature pertaining to aspects related to the study on the different curing regimes. In this section, aspects affecting strength of concrete are considered.

Part five concludes with the pycnometric portion of the study and includes notes on cement hydration, shrinkage and x-ray fluorescence.

2.1. Part One: Literature on General Aspects on Cementitious Materials

2.1.1. Cement Production

The production of cement involves finely grinding selected materials, proportioned to a desired quantity, before incinerating the materials to form a homogenous mix. The incineration temperatures can range between 1400°C and 1600°C in a rotary kiln (Islam, 2005).

The proportioning of the raw materials principally considers the amount of calcium, aluminium, silica as well as iron in the ore so that the desired cement characteristics are achieved (Gutterridge & Poweroy, 1983).

Initially in the kiln, the heat drives off the presence of any moisture in the raw meal together with carbon dioxide. The term calcination is ascribed to describe the putrefaction of carbon dioxide (Islam, 2005). The fuel to incinerate the raw materials could include making use of oils, gases as well as coal (Gutterridge & Poweroy, 1983).

With the formation of calcium silicate products, such as tri-calcium silicate (C_3S) and di-calcium silicate (C_2S), the term clinkering is ascribed. Packaged cement comprises ground

clinker which is speedily cooled after the process in the kiln and includes gypsum to regulate the setting characteristics (Islam, 2005)

Technical conditions applied in the kiln affect the performance of the final cement. Factors such as the incinerating conditions in the kiln affect the mineral phases that form. Some calcium hydroxide may not clinker and could remain as free lime (Harris, et al., 1988).

Some of the major minerals found in cement are listed (Lothenbach & Winnefeld, 2006):

Mineral	Short Hand Notation	Chemical Notation
Tri-calcium silicate	C_3S	Ca_3SiO_5
Di-calcium silicate	C_2S	Ca_2SiO_4
Tri-calcium aluminate	C_3A	$Ca_3Al_2O_6$
Ferrite	C_4AF	$Ca_4(Alxfe_{1-x})_4O_{10}$

Table 2.1.1: Common Minerals found in Portland Cement

The cost of producing cement extends to include the size and type of the kiln, the type of fuels as well as the technique and style of grinding. All these aspects pertain to energy consumption and utilization. The type of fuels can range from tires, animal residues to sewer sludge (Bolio, et al., 2011). The source of fuel could be a source of harmful trace elements and could affect phases that develop during clinkerization as well as hydration of cement.

Approximately two thirds of the cements in Europe are blended cements. The cements could include those containing a single blend of material such as CEM II A-V for instance. This cement would only contain fly ash. Multi blended cements such as CEM II A-M for instance could include as many as six extenders (Bonavetti, et al., 2011).

Limestone could be used in the raw meal in cement manufacture. Limestone could also be blended after clinkerisation. There would be implications on the manner in which limestone is used. For instance, in the latter technique, the fineness must demand special consideration. This aspect was noted by Bonavetti et al (2011) who explained that the degree of fineness of clinker would be different to limestone due to the different grinding abilities. Thus, the particle size distribution would be different and consequently, the hydration properties.

The use of extenders in concrete, such as fly ash, would be affected by a wide range of factors. For instance, the geological age of the coal and associated properties would be a

factor. The technique used to extract the fly ash would also be another factor and the efficiency would pertain to the available technology (Kruger, 1997).

2.1.2. Gypsum

Natural gypsum comprises of calcium sulphate. Two different forms exist, namely the di-hydrate form and the anhydrate form. The chemical notation associated with these two forms is (Karni & Karni, 1995): Di-hydrate: $CaSO_4.2H_2O$ and Anhydrate: $CaSO_4$.

Commercial forms of gypsum differ from natural forms of gypsum in different ways. For instance, natural di-hydrate is white or even colourless in certain instances whereas commercial di-hydrate may be greyish, brownish or even pinkish depending on the impurities present. The impurities can range from clays to irons (Karni & Karni, 1995).

Phosphogysum is a by-product from the manufacture of fertilizer. In China alone, approximately 90% is dumped in landfills. This material is capable of possessing cementitious properties in addition to working as a retarder (Huang & Lin, 2011).

One of the functions of gypsum in freshly cast concrete is to control the setting. The basic mechanism is summarised hereunder:

The hydration of tri-calcium aluminate (C_3A) present in cement may be undesirable as it causes flash setting upon contact with water (Deng, et al., 2012). For this reason, gypsum is incorporated into cement. In basic terms C_3A reacts with gypsum to form a calcium-sulphate-aluminate compound called ettringite. The ettringite contributes towards retarding setting of the cement thereby keeping the concrete workable (Baldini, et al., 1978).

The ettringite forms in small quantities gradually as time progresses. That is to say, all the gypsum does not immediately hydrate with C_3A to form ettringite. Instead, small quantities of gypsum react with C_3A to form small quantities of ettringite and this formation continues until the gypsum is consumed after which setting then results.

The ettringite formed from the reaction of gypsum with C_3A in the presence of water results in a layer or film that coats the C_3A molecules. This film is insoluble and hinders setting. However, when the film results, a small amount of water is likely to be entrapped with the C_3A molecule.

This small quantity of water will react with the C_3A molecule. The consequence of the reaction will cause an increase in the volume. The increase in volume will burst the film of ettringite coating the C_3A molecule.

The consequence of the broken film will allow for un-hydrated gypsum and C_3A to react and form ettringite. In turn, the processes described above repeat themselves. In summary, a film would coat un-hydrated C_3A. Water entrapped would react with C_3A resulting in a volume change which in turn would rupture the film and thereafter cause un-hydrated C_3A to react with gypsum. Once all the gypsum is consumed, setting results.

2.1.3. Fly Ash

Fly ash is a derivative from the combustion of coal. Some of the products from the combustion of coal include bottom ash, flue gas and fly ash. Some of the processes involved in order to source fly ash from the combustion of coal include separation of exhaust gases through making use of electrostatic or mechanical precipitators. Worldwide, the consumption of fly ash is a mere sixteen percent (Gikunoo, 2004).

Fly ash as a pozzolan could be feasible especially if the degree of fineness is high and the fly ash amorphous (Gikunoo, 2004). The ASTM 6618 classification system of fly ash, according to Shi and Qian (2003) interpretation of the code, comprises broadly two types of fly ash. Using the content of SiO_2+Al_2O_3+Fe_2O_3, Class F amounts to no less than 70% and Class C between 50 to 70%.

There are several factors which affect the suitability of a pozzolan. Some of the factors can include its ability to bind calcium hydroxide (also referred to as lime) and potential reactivity. A pozzolans reactivity depends on a number of factors which can be either chemically or mechanically related. Some of the mechanical factors can include the fineness of the pozzolan but could also include the curing periods as well as temperatures employed. The chemical aspects that affect the suitability of a pozzolan can include the chemical and mineralogical composition (Pavía & Walker, 2011). The state of the pozzolan may also be noteworthy. Walker and Pavia (2011) mention a ‘rule of thumb.’ They believe that amorphous states are more reactive than crystalline states.

2.1.3. Blast Furnace Slag

Blast furnace slag is a by-product of the iron making industry. It consists of the fusion of limestone flux, ash for coke fuel and siliceous residues and aluminous residues (Wolhuter, 1972).

The manner in which the slag from the furnace is treated after being removed is important with regards to hydration. If the slag is allowed to cool slowly, it will not yield to be useful as a cementitious material. If the slag is allowed to cool slowly, it would result in being very

crystalline (Wolhuter, 1972). Glass content of ninety percent or more are recommended but slags having less than this have also been found to show good performance as Li, et al (2010) mention.

If on the other hand, the slag is cooled with a stream of air or water jets after being tapped from the blast furnace at high temperature, the slag will cool much quicker. The consequence of this would be that crystallization would be prevented. Slag cooled in such a manner is often referred to as granulated slag as this slag appears beady and glassy and is much more reactive (Wolhuter, 1972).

Slag will not hydrate or harden on its own. It requires the presence of an activator such as Portland cement, lime, magnesia, sodium hydroxide, potassium hydroxide, alkali sulphates or mixtures of salts (Wolhuter, 1972).

Some of the comparative benefits of utilizing slag in concrete against using plain Portland cement include (Mahmud et al, 2012, p188):

(a) Reduction in pollution levels due to reduced amount of carbon dioxide generated to produce slag.

(b) Less effect on health when handling. This could be measured through inferring that slag reduces skin irritation. This may be attributed to the reduced levels of chromium.

(c) In terms of heat generated, lower heats of hydration result through incorporating slag into concrete. This aspect may be desirable when thermal cracking of mass concrete such as with dams are important to avoid.

Uzoegbo (1997) explained the many advantages GGBS has to offer. These included that the strength in the long term would be higher than usual. Also, GGBS would result in improved resilience against alkali, sulphate and chloride attack.

2.1.4. Silica Fume

Silica fume, also known as micro-silica is an extremely fine and siliceous material. It is derived as a by-product from the silicon industry involved in the manufacture of silicon alloys (Neville, 2008).

The average particle size is approximately 100 times smaller than that of cement. Silica can account for as much as ninety percent (Boddy, et al., 2003). Its surface area can be as large as 15 000-30 000 $m^2.g^{-1}$ compared to cement which is only between 300-500 $m^2.g^{-1}$ (Barati, McLean, Roy, & Sarder, 2011; Boddy, Hooton, & Thomas, 2003). Silica fume is

agglomerated in certain cases to increase in bulk density since silica fume in the loose state is difficult to handle (Neville, 2008).

Some of the enhancements that can result from using silica fume include improved early strength, densification and in turn reduction in pore size as well as an improvement in the bond between the interface between cement paste and the aggregate (Rao, 2003).

Silica fume should be used with care. Incorporating silica fume into concrete can lead to handling and placing difficulties as well as an increase in water demand and plastic shrinkage (Cail, et al., 1999). The plastic shrinkage is a consequence of a reduction in bleedwater that results as Neville (2008) ellucidates.

The large surface area associated with silica fume can result in a greater water demand in concretes that make use of silica fume. Such concretes can experience extended setting times due to the increased presence of water to satisfy the water requirements when silica fume is incorporated (Hocaoğlu, et al., 2012).

Neville (2008) provides notes on cautionary measures to take when mixing silica fume. The capacity of the mixer should be limited to just a half or even a third instead to ensure that the contents mix thoroughly. Furthermore, the time used for mixing should be long enough to also ensure thorough mixing. In addition, the sequence in which the materials are added into the mixer should be devised so that the procedure ensures complete and thorough mixing.

According to Ananmalay (1996), silica fume is not common in South Africa.

2.1.5. Ternary Blends

The use of two or more extenders in cement can enhance the properties of concrete. The enhancements can be realised in the fresh as well as hardened state of concrete.

Cail et al (1999) draws on the advantages that can be attained through exploiting the synergetic effect between silica fume and fly ash in improving the fresh state and hardened properties of concrete:

With regards to the fresh properties of concrete, the low workability associated with using silica fume can be offset through incorporating fly ash as fly ashes tend to generally improve workability.

With regards to the hardened properties of concrete, the low early strength associated in the early stages with fly ash can be offset through incorporating silica fume as silica fume offers

the advantage of high early strength. Durability improvements can also result through making use of ternary blends as the extenders can lead to reduced permeability.

2.2. Part Two: Literature on Chemical Aspects related to the Study

2.2.1. Analytical Chemistry

It is important to obtain a representative sample. An investigation of the representative sample must yield a meaningful indication of the bulk system being investigated. Thus, it can be appreciated that importance must be given to proper sampling otherwise there would be doubt on the actual behaviour of the bulk system (Kenkel, 2003).

Handling errors that may arise in an investigation necessitates a discussion on the type of errors that may be encountered. Broadly speaking, deterministic and indeterminate errors are relevant to discuss. Errors whereby the error carries forward due to wrongly calibrated equipment, impurities in reagents used if the study involves some analytical chemistry, poor technique in obtaining representative samples as well as errors that could be made in calculations classify themselves as deterministic errors. The use of statistics as a tool in establishing confidence limits and allowable limits of deviation for inter laboratory tests gives measurable criteria for handling indeterminate errors which are also known as random errors (Kenkel, 2003).

The percentage or concentration of certain constituents in a sample might be of particular interest. It might be better to sometimes study the sample in a liquid state than in a solid state. This deals with the field of solid liquid extraction. It involves dissolving the sample in such a way that the constituent of interest remains in a liquid form whilst other constituents remain in an insoluble form. This then allows the constituent of interest to be quantified independently from the other constituents (Kenkel, 2003)

An understanding of the nature and behaviour of the material is necessary when conducting extraction methods. For instance, correct selection of the solvent may often be simple water for materials containing heavy ionic salts or polar substances (Kenkel, 2003). Without delving into this field of research, it is reasonable to assume water as a solvent may not possibly be suitable for hydraulic binders, such as cement, since water would result in hydration and alter the dry state properties of cement.

In gravimetric methods of analysis, the samples under study are done by measurements of weight. On a similar note, volumetric methods of analysis utilize volume measurements as the principle to determine quantities (Kenkel, 2003).

2.2.2. Chloride

Internal sources of chloride are usually not problematic due to the impositions made by codes of practice and guidelines in the field of cement manufacture. Chlorides are of concern especially when reinforcement may be present in concrete. External sources of chlorides are more predominant and would be of greater concern than internal sources of chlorides in attacking reinforcement (Brouwers & Florea, 2012).

Polomark, Ramachandran and Seeley (1984) cite that chlorides in concrete could originate from internal sources such as through the use of admixtures or through external penetration.

Chlorides present in salts can include calcium chlorides and sodium chlorides. Sodium chloride is common in marine waters. The Persian Gulf is reported to have a concentration of 4.3% by mass. The Atlantic waters contain around 3.6% (Brouwers & Florea, 2012).

Chlorides as Polomark, Ramachandran and Seeley (1984) mention could be present in an insoluble form or in a water soluble form. The water soluble form is a much more dangerous form.

There could be, to some extent, a capturing of chlorides as they enter into concrete. C_3A and C_4Af are responsible for this arresting action and so, are beneficial in mitigating the effects of chlorides in attacking reinforcing steel in concrete. Several factors affect chloride capture and range from (a) the chloride concentration, (b) presence of mineral admixtures such as slag and fly ash (c) temperature (d) carbonation as well as (e) other aggressive agents such as sulphates.

Fick's law provides a means for estimating of the degree of chloride ingress in concrete over time. The content of chloride at the surface of concrete is required in using Fick's law (Walraven, 2012).

Chlorides internally available should result in greater chloride attack than chlorides having to diffuse through concrete from the external environment. Andrade et al (2012) had incorporated a high amount of 3% of chloride into the cement of their study in order to promote and accelerate chloride attack.

One of the noteworthy aspects of chlorides attacking reinforcement from a chemical balance point of view is that chlorides themselves do not combine in the reactions. The actually free themselves up and for this reason are dangerous as they can initiate further corrosion. (Song, et al., 2008)

2.2.3. Sulphates

Sulphate ions attacking cement paste may be from the external environment of concrete as well as internal sources of sulphates. Internal sources of sulphates could be from the constituents of the mix such as the aggregates, cement and admixture (Atahan & Dikme, 2011). Sulphur in aggregate can occur in a variety of forms such as pyrite (FeS_2), pyrrhotite ($Fe_{1-x}S$) or as sulphates and each form can have varying effects (Chinchón, et al., 1991).

Sulphate resistance depends upon several factors such as cement type, the concentration of sulphates and the period to which concrete is allowed to be exposed (Hossain & Lachemi, 2006).

On this note, as inferred from Irassar (2009), sulphates from acetic sources not only contribute to gypsum formation but depletion of CSH. This could result in total ineffectiveness of concrete once all the binder is consumed by such an acetic environment.

The presence of certain mineral phases in concrete such as C_3A and $Ca(OH)_2$ in the presence of sulphates may contribute to deterioration. The result of the reaction between such mineral phases with sulphates results in expansive products which could cause disintegration and sometimes, softening of concrete. Softening of concrete is also a form of deterioration (Hossain & Lachemi, 2006).

Irassar (1990) conveniently summed up sulphate attack as a three stage process. In the first stage, ingress of sulphates by solution occurs. In the second stage, the result of the ingress of the ions leads to formation of expansive products. The consequence of the attack, which is the third stage, is the deleterious effects that result.

$Ca(OH)_2$ that results from hydration could make cement vulnerable to sulphate attack. Just as well, high amounts of C_3A may also make cement susceptible to sulphate attack (Al-Amoudi, et al., 1995).

Irassar (2009) provided mitigation strategies of which, the incorporation of pozzolans could be a means for improving sulphate resistance. The effects of pozzolans assist with reducing

C_3A levels. The pozzolans incorporated in cement results in diluting the cement and explains the reduced effect of sulphate attack when a pozzolan is sued.

The hydration of C_3S results in the formation of CSH as well as calcium hydroxide. The calcium hydroxide is seen as a negative product in terms of sulphate attack. Sulphate attack already discussed leads to the formation of gypsum and the presence of calcium hydroxide is negative since it is one of the constituents of gypsum (González & Irassar, 1997).

Considering that pozzolanic reactions consume calcium hydroxide during hydration, it is no surprise then that mineral admixture such as fly ash assist with improving sulphate resistance. Pozzolanic materials also lead to a refined pore system resulting from consummation of $Ca(OH)_2$ and formation of additional CSH (Buffo-Lacarrière, et al., 2012; Hossain & Lachemi, 2006).

Low water/cement ratios are also useful to consider as a means to improve resistance to sulphate attack. Using low water/cement ratios results in reduced permeability (Buffo-Lacarrière, et al., 2012; Hossain & Lachemi, 2006). Other practical measures include ensuring good compaction and proper curing (Irassar, 2009).

One of the products that form from the attack of sulphates on concrete is that of Thaumacite, abbreviated as $CaCO_3.CaSO_4.CaSiO_3.15H_2O$. This product is destructive as it directly attacks the CSH component of hydrated cement. The presence of calcium carbonates ($CaCO_3$), moisture (H_2O), low temperatures and carbon dioxide aid the formation of Thaumacite (Bellmann & Stark, 2007; Aguilera, et al., 2006).

To conclude this section, it should be mentioned that careful consideration is demanded when reviewing sulphate attack. For instance, it has been mentioned that fly ash can mitigate the negative effects associated with sulphate attack. However, fly ash cannot resist against internal sources of sulphate attack in the early stages partly due to the slow hydration characteristics associated with fly ash (Chang, et al., 1988).

2.2.4. Insoluble Residue

One of the important aspects that may be inferred from this test is the quality of the cement. Arwui et al (2011) explains this facet in terms of "Adulterated" cement.

The description offered by Arwui et al (2011) on adulterated cements alluded to describing blending of cements with materials deemed as dangerous. This was the case since no

deliberation was prompted for the impacts of mixing cements with such materials in terms of the effects on strength and durability.

The dangerous items in the study of Arwui et al (2011) may be deemed as dangerous since blending cements with any material without scientific inquiry alters the chemical characteristics and performance. Arwui et al (2011) alluded to this fact through explaining that replacing portions of cement with flour, rock or dust might show satisfactory performance in the short term but would certainly have implications on the durability and life span of concrete and the problems of durability could be exacerbated with extreme events in nature such as hurricanes and typhoons.

Jaturapitakkul et al (2000) explained that the insoluble residue parameter may be a means of inferring the degree of adulteration in cement. Even more, there is mention that one of the main sources of insoluble residue arise from contaminants found in gypsum.

Awol (2011) mentions that hydrochloric acid is used to treat cement in order to infer the degree of cement adulteration. This shows that the materials remaining after dissolving in hydrochloric acid would be the portion that would contribute the least to strength development since if hydrochloric acid cannot dissolve it, surely water would not.

Important findings in the study of Jaturapitakkul et al (2000) included that the setting times and compressive strengths were not significantly affected for the various mixes that were developed to artificially simulate varying degrees of insoluble residue.

In the literature review of the study by Jaturapitakkul et al (2000), the authors aptly cited the work of Neville (1982) who wrote that modern cements have greater percentages of calcium silicate (tricalcium silicate in particular) as well as larger specific surface areas resulting in greater strengths than cements made in the past. Thus, the insoluble residue being quartz, which is a non-cementing material as the authors alluded to, had insignificant effect and the authors even suggested that the limits prescribed in the codes could be increased (Jaturapitakkul et al., 2000).

SANS 50197 (2000) dictates that the insoluble residue ought to be limited to under 5% for any of the strength classes (32.5, 42.5, 52.5 Normal or rapid hardening) of CEM I and CEMIII respectively.

Several authors have described insoluble residue as a non-cementing component in cement that must be limited in cement due to its negative effects on the development of compressive

strength, especially early strength development (Jayamanna, Ranathunga, & SSiriwardena, 2010; Abeyruwan et al., 2012; Ali & Amin, 2010; Hani, 2011; Ali, Hossain, & Khan, 2008).

Insoluble residue limits are stipulated by various codes including the Sri Lankan and British codes used by the afore mentioned authors and the importance of the presence of a non-cementing component is to do with the quality of concrete. For reasonable surety on the safety of structures as well as to avoid loss of life or damage to property resulting from poor quality concrete, specifications have been developed.

In the study of the afore mentioned authors on insoluble residue limits, only ordinary Portland cements had been tested. SANS 50197 (2000) only requires that ordinary Portland and slag cements be tested for insoluble residue and not for any other type of cement. The reasons for this were unclear at the time of investigation.

Abeyruwan et al (2012) tested a fly ash cement and found that the amount of insoluble residue exceeded the limit given in the code. Though no reasons were given, the author mentioned that since the cement was a fly ash blend and no requirements on the codes are provided for blended cements, the high insoluble result was expected and considered to be acceptable.

In most of the studies of the afore mentioned authors who compared the performance of cement from various manufacturers, it was found that the insoluble residue limits satisfied those stipulated in the respective codes, typically under 1.5%.

For an indication of insoluble residue values of various materials, the report of Lam et al (2011) is useful: (a) Bottom Ash-11.7%, (b) Fly Ash-22.8%, (c) Sewer Sludge-3.0%, (d) Limestone-40.4%, (e) Sand-8.6% and (f) Copper Slag-0.2%.

The percentage of insoluble residue in a cement mix may be indicative of the content of fly ash in a blended cement mix. Techniques to determine the percentage of fly ash can range from Gamma ray spectrometry to measuring the natural radioactivity of samples. A simple relationship on the level of insoluble residue however can be of benefit possibly for economic and routine testing to assess the level of fly ash:

$$\%\text{Fly Ash} = \frac{\frac{Mass\ of\ insoluble\ residue * 100}{mass\ of\ sample\ in\ test}}{\%\ difference\ of\ insoluble\ residue\ of\ fly\ ash\ and\ plain\ cement} * 100$$

(Fan, et al., 1992)

2.2.5. Alkalis

The introductory remarks of He and Li (2005) draw to the attention of the reader the importance of considering alkalis even though they may appear to be present in small quantities as these can have significant influence on the microstructure and early age cracking properties of concrete. The small quantities are collectively recorded as Na_2O equivalent and are evaluated from summing the quantity of Na_2O to $0.64K_2O$. Typical values ranges between 0.3 and 1.5%.

Some of the concerns surrounding alkali silica reaction are those related to expansion. Indeed, Hobbs (1988) details a South African method which exploits the negative effect of alkalis in causing expansion to assess the susceptibility of potentially undesirable aggregates, i.e. aggregates that may contain free alkalis that can cause disintegration and cracking through expansion. Briefly, the method involves noting length changes on prisms cured at high temperatures in an alkali solution (sodium hydroxide solution) over 14 days and a stipulated length change criteria limit of 0.2% is made use of to classify aggregates as being very much dangerous to alkali attack.

Alkalis susceptibility may arise from aggregate containing silica such as quartz and opal (though quartz may be more stable compared to opal and thus less volatile in causing deterioration) as well as in actual cement due to the presence of such alkalis contain in raw meals of limestone and clays which are typically required for the manufacture of cement (Hobbs, 1988).

From Hobbs (1988), simplistically, the cause of expansion and in turn the cracking and disintegration associated with expansive products resulting from the reaction of alkalis with hydroxyl ions which lead to the formation of alkali-metal-ion-hydro silicate products Thus from the afore mentioned hydration product, it can be gathered that conditions necessitating the formation of such an expansive product would include, the presence of alkalis, ions such as hydroxyl ions, moisture (hydro) and a source of silica (“alkali-metal-ion-hydro silicate”).

Some technique with basic principles to avoid the involved consequences of alkali attack can offer the concrete technologist opportunity to sagely prevent against the cause of such species in concrete. One obvious principle to make use of is prevention, i.e. to avoid susceptible aggregate (Hobbs, 1988). Identification as a principle to avoid the effects of alkalis leads us to consider the work of Carey and Guthrie (date) who proposed a novel petrographic

technique involving making use of dyes that stain regions in concrete which aids in visually identifying regions of concrete that has been affected by alkalis.

The use of pozzolanic materials such as fly ash and GGBS cannot go without note as such materials have, according to the survey of Fernández-Jiménez and Puertas (2002), the ability to limit hydroxyl ions and consequently, reduce the effects of alkali attack. Also of interest from the study of the authors, who succinctly point out that often enough, pozzolanic materials are accompanied with alkali activators in cement. Whilst the typical levels for alkalis may only approximate to 0.8%, the inclusion of alkali activators can be as high as 3%. Nonetheless, despite such significant proportions (in this case, 275% increase relative to the content of cement without an activator), the effects of pozzolanic materials have still been found to have beneficial effects in limiting alkali attack. From the work of Hobbs (1988) and Fernández-Jiménez and Puertas (2002), such extenders have the potential to limit moisture and transport and consumption of $Ca(OH)_2$ and thereby invariably reduce alkali silica attack.

2.3. Part Three: Literature on Aspects related to Physical tests in the Study

2.3.1. Setting

The setting of concrete is a practical concern for concrete cast on site. One way of grasping the concept of setting time is through relating the transition of fresh concrete to its hardened state whereby minor loads are capable of being sustained (Eren & Marar, 2009).

The range of factors on the setting extend to include temperature and humidity levels, the mix design, as well as the effect of mineral composition on the cement (Mamlouk & Zaniewski, 2006).

From a chemical perspective, the setting of cement relates to formation of hydration products which lead to stiffening. This can be inferred from the work of Hand, et al (2008) whose work explains an important aspect in setting, namely, delayed setting. From their work, it is gathered that the presence of heavy metals such as lead, zinc and tin can serve to coat cement grains and hinder water from reacting with un-hydrated grains of cement. This in turn ceases the formation of CSH and calcium hydroxide and thus explains the delay of setting.

Standards such as EN 196-3 (2005) evinces the use of a Vicat apparatus to determine the setting of cement. The nature of the test involves noting depths of penetrations by precisely manufactured needles from which the times of initial and final setting times are inferred (Amziane, et al., 2010).

The setting of cement can also be determined through other simple techniques such as Gilmore needles or more sophisticated techniques such as impact echo, pulse echo, ultrasonic pulse velocity, wave reflection and microwave absorption techniques. Penetration methods are limited by the skill and experience of the operator (Scherer et al., 2012; Bosiljkov, et al., 2008).

The use of gypsum, be it naturally occurring gypsum, phosphor gypsum or synthetic gypsum as a building material is realised in adhesives products, jointing and filling compounds, cement as well as plasters (Arikan & Sobolev, 2002; Potgieter & Strydom, 1999).

The presence of gypsum ($CaSO_4.2H_2O$) is beneficial as an agent to control the stiffening of cement. One of the mineral phases that cause stiffening of cement is that of Tricalcium Aluminate (C_3A). In the presence of Portlandite ($Ca(OH)_2$) and water, C_3A reacts to form Calcium Aluminate Hydrate (C_4AH_{13}) which is responsible for the stiffening (Bhatty, 1987).

Also, Ettringite ($C_3A3CaSO_432H_2O$- (Bellmann & Stark, 2007)) forms after gypsum reacts with tricalcium aluminate (C_3A). The ettringite results in an impermeable film that surrounds cement grains. Thus it forms a barrier for water to form hydration products and in doing so, controls the setting of cement (Lianzhen, et al., 2006).

The chemical state of gypsum is important. The formulation of gypsum ($CaSO_4.2H_2O$) is due to the combination of sulphates (SO_4^{2-}) with lime ($Ca(OH_2)$) and water (H_2O). If it is present in cement as hemihydrate ($CaSO_4.\frac{1}{2}H_2O$), perhaps due to the effect of high temperatures at the mill when gypsum was being ground as temperature can drive off moisture, it would react with water to form di-hydrate-gypsum ($CaSO_4.2H_2O$) instead of ettringite. This in turn, would result in rapid stiffening or a flash set (Cohen et al., 2003; Potgieter & Strydom, 1999; Lianzhen et al., 2006).

A summary of the factors influencing setting time extends to include (Thomas, 2013): (a) composition of cementitious materials present, (b) fineness, (c) presence of admixtures, (d) quantity of water, (e) environmental factors.

To elaborate upon the factors, the composition of the mix can result in either a delay or an acceleration of setting. For instance, low calcium fly ashes and slags tend to prolong setting times. In cases where environmental factors can be severe such as with cold temperatures, this can be seen to be of a disadvantage and could even require special precautions as concretes containing these extenders can possibly freeze.

High temperatures make handling, compacting and finishing concrete on site difficult. This is explained by Ahmadi (2000). Hot weather climatic conditions may result in a demand of water and at the same time accelerates slump loss together with setting times.

2.3.2. Loss on Ignition (LOI)

Chusilp et al (2009) exploited the LOI technique to investigate the influence of bagasse replacement on the sulphate resistance of Portland cement blends. Geiker et al (1990) and Bentz (2006) had found that the LOI could be beneficial in monitoring hydration with time.

It can be gathered that the igniting of a sample of material can be exploited to infer a wide variety of properties ranging from the organic matter in soils, resistance to chemical attack and hydration as noted by the studies of the above mentioned authors.

The ignition of a cement sample would result in driving off any water and carbon dioxide present (Fraaij, et al., 2006). The results of such an exercise can be used to infer the degree to which the cements may have hydrated during the period in which the cements were manufactured and the period of storage as well as the detrimental effects that carbon has on cement.

If there are sufficiently high quantities of iron mineral, it could be possible that the results of the LOI would reveal a weight gain in the ignited samples due to oxidation. In the study of Costa et al (2010) it was noted that magnetite present can be converted to hematite during oxidation. This leads to weight gain as the properties of hematite in terms of weight is greater than the former.

2.3.3. Specific Surface Area

Depending on type of cement and purpose amongst a whole range of other factors, cement fineness (in general terms) is approximately $350m^2/kg$ as Gutterridge and Poweroy (1983) evince and further note that most particles (90%) would pass a 45micron sieve.

Usually, the value of fineness, expressed as area in meters squared per kilogram, is by surface area and could be measured by means of an air permeability test (Gutterridge & Poweroy, 1983).

Increasing the degree of fineness of supplementary materials may improve early age strength development. Though reaction rates may be accelerated with increased degrees of fineness, adverse effects such as increased water demand and accelerated setting times could be the consequence (Chen, et al., 2011).

Concretes containing admixtures such as slags can achieve similar strengths to ordinary concrete without slag through carefully selecting and proportioning the mixture of materials in the concrete (Babu & Kumar, 2000). On this note, supplementary cementitious materials such as slag, fly ash, silica fume or even limestone and metakaolin ground finely enough can lead to high strengths in part due to the filler effect that results (Chen & Kwan, 2012).

Chen and Kwan (2012) cite from several studies the effects of ultrafine grinding of cementitious materials and note that with regards to workability, the effects of (a) silica fume revealed reductions in workability, (b) slag materials showed minimal effects but (c) fly ash materials sometimes showed improved workability and at other times reduced workability.

High degrees of fineness may promote early strength development, however, in the long term, perhaps after twenty eight or ninety six days of hydration, strengths achieved between specimens with high degrees of fineness compared to the controls reveal similar strengths (Barbarulo & Termkhajornkit, 2012).

The method in which blended cements are ground may affect strength development. When blast furnace slag is ground separately from the clinker, better strengths can be achieved than when the clinker and slag are interground. The relative hardness of the particles between the two materials may be one of the factors that results in reduced efficiency in grounding clinker and blast furnace simultaneously. For this reason, grinding blast furnace slag separately from clinker and then blending could be better suited since the finer the blast furnace slag, the greater the reactivity which, in turn, contributes to better strength development (Erdoğdu et al., 2003).

2.4. Part Four: Literature on Aspects related to Studies on the Curing Regimes

2.4.1. Curing

The temperature and moisture levels are important factors in curing and to ensure quality concrete. Ensuring sufficient moisture for hydration is clearly important for hydration reactions considering that Portland cement is a hydraulic binder. The techniques for curing may be as rudimentary as ponding a surface of fresh concrete to minimize moisture loss to employing chemical compounds. From an industrial vantage point of view, the minimum period of curing is beneficial for increasing productivity (Rao, et al., 2010).

Inadequate curing may cause poor durability due to permeability. Considering that GGBS and fly ash develop strength slowly over time, providing extended periods of curing may be

necessary for adequate strength and durability (Razak & Sajedi, 2011). Good curing is essential where specimen size and volume is large as with slabs since such large items can possibly dry out (Brito, et al., 2011).

Over extended periods of time, moisture loss in concrete may pave the way for atmospheric carbon dioxide to react with lime present in concrete and subsequently form hydration products which occupy larger volume than the original constituents. Such an establishment may hinder available water from reacting with un-hydrated cement to form additional CSH (Ballim, 1994).

The effects of inadequate curing would depend on the type of concrete. Ceasing curing (perhaps through removing moisture by drying out the concrete in an oven) in low strength mixes where the volume of capillary voids is large may not be as serious as with high strength concretes. In high strength concretes, the capillary networks may collapse and become discontinuous upon removing water but in low strength mixes the large volume and network of capillaries would allow for hydration to be resumed (Jardine, 1976).

Medium capillary pores range from 10-50nm diameters. Gel pores could be less than 10nm in size. Large capillary pores could range between 50 – 10 000nm. The permeability of concrete can be reduced through the incorporation of fly ash or other pozzolans which tend to react with portlandite leading to the formation of additional CSH. This leads to enhanced durability since the permeability is reduced (Chindaprasirt, et al., 2007).

The effects of high temperatures in the early stages of concrete may result in enhanced strength compared with lower curing temperatures though in the long term, strength development could be reduced. In terms of the effects of high temperatures on the rheological properties of cement, it would be observed that reduced workability and accelerated setting times result (Aguado, et al., 2009).

The reduced ability of water to react with un-hydrated grains of cement due to the already hydrated cement which forms a barrier may explain the reduced overall strength in the long term when high temperatures are employed (Lin & Meyer, 2009).

Razak and Sajedi (2011) better explain the reduction of strength development in the long term through explaining that when temperatures are high, increased hydration rates may be promoted but the hydration products that forms do not arrange themselves in an orderly and adequate fashion. As time proceeds, this poor arrangement and placement of hydration products works against allowing further hydration products to institute.

High temperatures in the early stages used with the intention of promoting early high strength can cause deterioration at later stages in the concrete. When temperatures exceed seventy degrees Celsius, a phenomenon known as delayed ettringite formation may prevail. Ettringite is one of the products that result from the hydration of cement, however, when this product forms in the hardened state of concrete, the consequences can be severe deterioration (Thomas, 2013).

2.4.2. Climate

Since the present study was conducted in Johannesburg, it is appropriate to provide some notes on the local climate of Johannesburg.

The wind patterns as is understood from Goldreich (1969) vary throughout the year for Johannesburg. In summer, it can be expected that the direction of wind around midnight is first North Easterly and Westerly in these months respectively. At around 8am, the course of winds blow Northerly and North-Northerly. In summer, from the morning up to mid-afternoon, the winds continue to blow north but mean maximum speeds at 9am are the most fast. The period of the day with the slowest wind speeds are in the evening at 6pm.

The overall portrayal of weather provided by Goldreich (1967) for summers in understood as a month of warm temperatures (minimum and maximum temperatures ranging between 14 and 24.6˚C) with possibility of violent thundershowers in the early afternoon and evening periods but dry and cool winters with between 5.4 and 16˚C.

2.4.3. Workability

Brito et al (2011) proportioned the materials in their study so as to achieve the same workability and motivated for such an approach through mentioning that this would be what the end user on site would do. This case demonstrates that workability considers a number of items that the operator on site must consider. These items would include that the materials can be mixed with ease, placed appropriately, moulded into the desired shape and compacted properly (Thomas, 2013).

Workability of concrete must consider the type of application that is required. For instance, in high strength concrete, low water cement ratios may affect compaction and placing but the incorporation of plasticizers are often employed along with careful consideration of aggregate size and possibly high cement quantity (Addis, 1999).

All this may lead to improvement in workability of such high strength mixes making use of low water to cement ratios. The type and size of specimen to be cast may demand varying workability states. As an example, regions of high densities of reinforcement would demand more workable mixes than mass concrete elements such as a dam (Jardine, 1976).

The manufacture of items such as paving blocks, roofing tiles and curb stones requires close to zero slump values as such mixes need to be dry enough so that the moulds used can be turned around for high production. The mixes need to be dry enough to stand on their own after the compaction is applied in the mould (Brouwers & Hüsken, 2012).

Aggregate properties are also important to consider with regards to workability. One of the important properties to consider is the presence of fines in the aggregate (Thomas, 2013). Supposing this to be the material passing the no 200 sieve, has the tendency of reducing workability. In addition, the presence of fines can lead to reduced bleeding, improved cohesiveness as well as a reduction in the air content but excessive quantities may hinder aggregate cement bond development (Bonavetti & Irassar, 1994; Eren & Marar, 2009).

The cementitious properties are also important to consider. As an example, the presence of high fines content in fly ash serves to improve workability through reducing particle interference (Thomas, 2013).

Some of the consequences of poor mix design are bleeding, segregation and honeycombing (Miao & Su, 2003).The influence of hot temperatures and wind tends to reduce workability through evaporating water in fresh concrete. This in turn reduces workability, making it difficult to cast, compact and finish concrete. Retarding admixtures would prolong hydration. Making use of such a chemical additive would be desirable in situations where there is risk of reduced workability due to high temperatures or where strong winds may promote water loss from concrete (Ravina & Soroka, 1998).

Caution should be exercised in using extenders to prolong setting and hydration of fresh concrete in order to maintain adequate workability. Extenders such as fly ash may contribute towards plastic shrinkage which can be associated in certain circumstances with cracking (Ravina & Soroka, 1998).

2.4.4. Strength

Cotsovos & Pavlović (2008) explain the development of stresses in concrete when concrete is subjected to externally applied loads. A tri-axial field results when external load is applied and is responsible for maintaining resistance to the external load. The development of cracks

internally results in voided regions in the concrete and stress concentrations. Such concentrations in concrete can result in possible local failure. Bearing in mind concrete to be a porous material, from the perspective of volume of voids, the detrimental effects of the presence of around 5% can be severe and as Jardine (1976) surveyed from literature, a reduction of as high as 30% in compressive strength may be the consequence.

In evaluating the performance of a mix design in terms of strength, the geometrical dimensions of test specimen moulds used in the study may affect the interpretation of the results. Moisture loss is clearly detrimental and should be protected against. From the perspective of specimen size, the effects of moisture loss perhaps from evaporation effects would be more pronounced in test specimens of small cross section than in specimens of large cross section. The importance of moisture in sustaining hydration reactions is clearly important for continued strength development. This aspect can be understood through attempting to visualize the effort that would be required to drive out water from a large test specimen as opposed to a small sized specimen (Baradan & Un, 2011).

Achieving high strengths of the order of at least 60Mpa, typical of high strength concrete after 28days of curing may be achieved through careful selection of chemicals such as plasticizers and cement type, making use of low water to cement ratios and coarse fraction of aggregate between 10 and 12mm (Addis, 1999).

Assessment of the strength of concrete should reveal variability due to a number of factors ranging from variations in properties of materials, even between batches, the procedure for sampling and handling conditions. The acceptance of test results from a number of studies resulted in establishment of statistical parameters to aid the consultant. One such finding from Cook (2002) is that of basing strength values between samples not differing more than 6.9 MPa as a criterion.

With regards to testing for strength, factors such as the loading rate, the surface texture, creep and bleeding effects can affect the strength. The faster the loading rate, the greater the strength results that would result than if the cube were to be tested slowly (possibly due to crack propagation and spread). A dry cube would exhibit greater strength compared to a cube whose surface is moist due to the increased friction between the loading platen and surface of the cube. Creep allows for stresses internally to unify and spread so as to achieve a distribution internally. The effects of bleeding can result in weakened planes especially near

the surface due to higher water/cement ratios resulting from increased water from bleeding (Stanley, 2006).

2.4.5. Mix Design

Depending on the application, cements can be blended and proportioned in different ways to suite a wide range uses.

To illustrate the advantage that cement can have with regards to being blended with other materials, a nuclear example is provided. Cements may be a preferred material for shielding radioactive wastes due to its relatively low cost and radiation stability but has issues of high leaching (Dimović & Plecas, 2006). The hydration products such as calcium silicate hydrate and ettringite can tie up wastes (Gougar, et al., 1996).

A possible solution to the high leaching associated with cements could be to blend the cement mix with bentonite clay. The bentonite clay in this example serves to reduce the high leaching property associated with cement. One of the reasons for the enhancement of reduced leaching may be due to the low hydraulic conductivity and its state of electric charge (Dimović & Plecas, 2006).

Careful selection of the choice as well as the proportioning the materials is important depending on the application. For instance, with high strength concrete, the use of selected cements and aggregates are decided in such a way to achieve high strength. Such a mix is likely to make use of low water to cement ratios coupled with super-plasticizers as well as aggregate that has a low water demand (Addis, 1999).

For specialised laboratory studies as with microscopy of concrete, Ananmalay (1996) proposed using dolerite aggregate as dolerite has distinctive features that make it easy to distinguish in such analysis.

2.4.6. Durability

Castro-Gomes and Torgal (2006) provide a simple definition of durability. Essentially, durability involves concretes resilience to attack be it from the environment, from physical means (such as abrasion) or chemical sources (such as chlorides and sulphates).

Strength, as Wasserman and Bentur (2012) note, is one of the means to assess the influence of curing. They further mention that the quality of concrete should not only be assessed through strength but should also include durability testing. In their study, three different curing regimes revealed similar strength for environments simulated to depict harsh and mild

environments but found significant discrepancies for air permeability tests which were used to infer durability.

Adenot et al (2007) relate permeability to durability and explain that agents affects durability such as carbon dioxide may permeate into concrete through diffusion, pressure gradients as well as concentration gradients. The permeability arising due to the connectivity of pores, pore size are amongst the considerations and extend to include factors such as the type of cement, curing conditions, water/cement ratios and aggregate proportions.

With regards to aspects of the microstructure structure, it is inferred from Chen and Wu (2013) that there is a presence of air voids, capillary voids as well as gel pores whose distribution and structure is irregular.

Studying aspects on the structure of the pore network such as pore size and distribution can be challenging. Certain techniques can result in altering or potentially even damaging the pore network. Pre-treatment may be required in certain tests such as drying of specimens before testing which could also affect the pore structure. The microstructural features may be quite different for sections of cement paste compared to sections of interfaces of cement paste-aggregate sections. For an appreciation of the scale of pore sizes, those that are under 2nm are considered to be micro pores (CSH would be categorised herein), macro pores are those whose size exceeds 50 nm and meso pores range in between the bounds established for micro and macro pores. Capillary pores can range from 2 to 10 nm (Aligizaki, 2006).

Durability consideration from a holistic approach offers benefit to the serviceability that can be attained in design. The interaction of a structure with the environment, the materials involved in construction, the loads that the structure have to bear are beneficial aspects to consider in order to optimize the service life of structures as Kargol et al (2013) inform. On the note of service life improvement and enhancement, the use of surface protective coatings and impregnating agents would be welcome due to the improved resistance to the ingress of harmful agents such as chlorides and sulphates.

Also important in durability are the components of concrete. From Gomes and Torgal (2006) motivation for this is apparent considering that the coarse fraction of aggregate can account for up to as much as 80% of the total volume of a mix design. Furthermore, from the authors review, aggregate may possess a certain degree of micro cracks and porosity. Also, due to the contact between cement and aggregate in concrete, the so called interfacial transition zone may have a bearing on strength, stiffness and durability (Kockal & Ozturan, 2011).

Good durability design extends to include selection of the appropriate materials, envisioning the types of deterioration that might prevail as well as ensuring quality control during the mixing and monitoring of the concrete (Thomas, 2013).

2.4.7. Bleeding

As soon as water is added to cement, there is a period termed the dormant period during which freshly cast concrete can be worked before stiffening results. Bleeding is the term used to describe the upward movement of water in freshly cast concrete. One of the processes that contributes to bleeding is settlement. Concrete comprises of a range of materials including cement, sand, stone and water. Due to the differences in densities, the heavier particles have a tendency to settle and in doing so, force water to migrate upward (Rey & Wainwright, 2000).

Bleeding is important as it can adversely affect strength and durability. With regards to its effect on strength, the water/cement ratio may vary throughout a concrete section. The portion where there is a high water to cement ratio such as the near surface regions where bleed water rises to will have reduced strength (Rey & Wainwright, 2000).

With regards to durability, bleed water may affect concrete negatively. Bleed water contributes towards forming capillary networks that lead to inferior durability in concrete (Rey & Wainwright, 2000). Water entrapped under reinforcing as a result of bleeding can lead to reduced bond between the reinforcement as well as contribute towards corrosion as water is one of the requirements for corrosion (Rey & Wainwright, 2000; Ait-Aider & Wainwright, 1995)

The rate of bleeding reduces as time progresses due to the formation of hydration products which hinder the movement of bleed water. Extenders such as blast furnace slag can contribute towards bleeding if such extenders prolong the formation of hydration products through prolonging the fresh state of concrete (Rey & Wainwright, 2000).

Retarders, poorly graded mixes, low cement content as well as high water to cement ratios are further examples of factors that contribute towards bleeding (Ait-Aider & Wainwright, 1995).

2.5. Part Five: Literature on Aspects Related to Pycnometric Aspects in the Study

2.5.1. Pycnometers

Davis (1975) explained that for any period, it would be possible to infer the hydration of a mix through monitoring the amount of water absorbed by the mix. (Ballim, 1983) issued a

similar note as Davis (1975) through explaining the contraction of cement over time as water gets absorbed by the cement could be exploited to infer hydration rate and the degree of hydration.

Ballim (1983) followed the water absorption characteristics in order to assess the effects of two types of aggregate in concrete strength development. Davis (1975) exploited the setup to follow slag cementitious systems.

The items required for pycnometer studies could be regarded to be simply and affordable as had been noted by Davis (1975) and (Ballim, 1983)who had employed the simple technique to follow the water absorption of the respective mixes under investigation.

The test requires a single 500ml glass jar for each mix, a lid comprised of a metal ring and glass plate to seal the system. The glass plate is drilled and fitted with a graduated pipette. Water was filled into the jars up to the level of the burette in order to follow the amount of water absorbed over time.

2.5.2. Hydration

Simplistically, the stages of hydration may be thought of as a three way process on a time scale with each time frame distinguished by an early, middle and late stage. The early stage is characteristically short and involves rapid chemical dissolution of the cement upon contact with water whereby ions such as potassium, sodium, calcium, hydroxyl and sulphates dissolve into the water (Li & Xiao, 2009). The middle stage, given the name Induction stage, involves ion transport from a chemical perspective. The third stage is involves diffusion reactions over time during the remaining of hydration reactions (Lin & Meyer, 2009).

The hydration of cement is dynamic and involves different compounds, reacting at different rates and undergoing different phase changes as Wang and Yodsudjai (2013) note. Upon contact with water, C_3S reacts instantly with water and MacLaren and White (2003) cite the period as short. They then explain a period of decelerated activity, the induction period and mention that opinions vary as to the reasons for such behaviour. One school of thought attributes the formation of CSH resulting in an envelope that limits water to hydrate C_3S whereas another school believes the fact that calcium hydroxide resulting from the initial hydration causes the solution to become supersaturated. This then limits dissolution but over time, possibly several hours, the calcium hydroxide crystallizes which then allows for the reaction of C_3S to proceed.

The silicate phases, namely C_3S and C_2S may account for as much as 75% of the mass of cement. The main hydration products of the silicate phases, namely calcium silicate hydrates (CSH) and Portlandite ($Ca(OH)_2$) contribute approximately 57.5% (+/-7.5%) and 22.5% (+/-2.5%) (Aligizaki, 2006). Portland cement may also contain appreciable amounts of sulphoaluminates (Akyuz & Oner, 2007).

The lime fraction, $Ca(OH)_2$ is not a significant contributor to strength. Thus, incorporating pozzolanic materials are beneficial as such materials consume lime to form secondary CSH (Akyuz & Oner, 2007).

The complexity of cement phases such as Alite may encompass as many as seven different forms some of which as the hombohedral, monoclinic and triclinic types. Belite as well may have different forms such as monoclinic and beta forms (Gutterridge & Poweroy, 1983).

The description of CSH as portrayed by several researches which Aligizaki (2006) summarize includes that the substance can be fibrous, irregular, small in size (around 0.5 nm) and amongst other things, gel like.

The hydration of supplementary materials such as slag may exhibit pozzolanic and latent characteristics. Pozzolanic reactions involve the reaction with Portlandite ($Ca(OH)_2$). This aspect Massazza (1993) extends to include cover (a) the quantity that the pozzolanic material can combine with and (b) the rate of combination which may be dependent on the degree of fineness, temperature and the silica content. The reactivity as Alex et al (2008) points out is influenced by factors such as the slag composition, its amorphous glass content and degree of fineness.

The presence of a high alkaline environment in concrete containing slag is much desired for hydration of extenders such as fly ash and slag as such an environment hinders the formation of a film that develops around grains of slag during hydration. The film acts as an external insoluble layer comprising silica and alkali earth hydro silicates and has the negative influence of hindering hydration through impeding water absorption of slag grains (Claisse et al., 2011; Brouwers & Chen, 2010).

Other means of activating slag besides alkalis include the cement itself in a blended slag cement mix, sodium silicates, sulphates and calcium hydroxides (Buffo-Lacarrière et al., 2012). In the short term, slag blends may display delayed setting and low strength but in the long term, denser microstructural features and higher strengths may be afforded (Shi, 2004).

The presence of moisture is thus important for strength development and on this note; the degree of hydration and the rate of hydration is very much affected by the selected water: cement ratios. Low water cement ratios of the order of 0.4 or less as Lin and Meyer (2009) suggest would result in incomplete hydration of cement. They also make mention that high water: cement ratios promote hydration reactions in early stages in addition to affecting the overall total degree of hydration.

Accelerated hydration can be achieved through making use of cement with greater degrees of fineness as a greater degree of fineness promotes a greater surface area of grains in contact with water (Lin & Meyer, 2009). Whilst increasing the fineness may result in enhanced strength, the negative consequence could be an increased demand for water in a mix. This in turn could result in greater degrees of drying shrinkage if forced to make use of higher water contents perhaps for workability (Razak & Sajedi, 2011).

There are several techniques that can be used to monitor hydration. Some of the techniques include (Boncoeur, et al., 2003): (a) x-ray techniques such as x-ray diffraction, (b) thermal techniques such as differential thermal analysis, (c) nuclear methods such as nuclear magnetic resonance.

2.5.3. Water

The water content present in concrete can be explained in terms of three general terms, viz. water that is chemically bound, physically bound, or 'free' water. Chemically bound water is the water that has reacted with cement and is a part of the actual structure of the hydration products. Physically bound water is water that adheres firmly to the surfaces of the hydration products whereas bulk or free water is the portion of the water stored in the capillaries and pores of the cement paste (Baroghel-Bouny, et al., 2013).

2.5.4. Shrinkage

Shrinkage is a time dependent phenomenon that may induce strain in concrete. There are different types of shrinkage ranging from dry shrinkage, plastic shrinkage, carbonation shrinkage and autogenous shrinkage (Chilwesa, 2012).

As hydration occurs over time, un-hydrated cement in concrete may consume water available in pore spaces. The loss of water in such pore spaces can result in autogenous shrinkage (Boshoff, 2007).

The use of low water to cement ratios may lead to desiccation and autogenous shrinkage due to the creation of empty pores that result over time as cement hydrates. Light weight aggregate, due to its porous nature may provide for a replenishing supply of moisture to cement paste (Bentz & Snyder, 1999).

The absorbed water in lightweight aggregate can serve as a supply source for internal curing as Kaszynska (2012) denotes and adds that the usefulness can be realised through reduced cracking due to reduction in shrinkage and heat liberation due to the absorbed water in lightweight aggregate.

The notes on shrinkage have been provided to complement the comments made by Fulton (1964) who had mentioned that in the absence of water, the shrinkage of concrete would result and would be a measurable amount. In the presence of continuous water supply for hydration, the supply of water would serve as a replenishing source in the same way as lightweight aggregate would serve as a reservoir to prevent internal drying and in turn contraction. This is the basic idea behind using the pycnometric apparatus to follow the course of hydration for cementitious systems.

2.5.5. X-ray techniques

The use of x-rays along with exploiting the potential of atoms that excite upon contact with x-rays can be employed to determine the elemental compounds existing in a sample as is the case with x-ray fluorescence. Elements containing atoms, when excited by x-rays respond by emitting secondary beams. Carefully recording the secondary beams in a spectrum can lead to interpreting the different elements in a sample due to the different atomic numbers for different elements (Klockenkämper, 1997).

An analysis for the compounds in a material such as rock or cementitious material through x-ray fluorescence may be done through preparing pellets or beads. Testing beads may be preferred than pellets since the particle sizes and varying mineral composition can be a concern. In a bead, the sample is wholly decomposed to form a glassy flux which may be more homogenous and uniform (Austen & Russell, 1974).

2.5.6. Mineralogy

An appreciation of the composition of the cementitious materials in concrete may provide a better understanding of the materials contribution to fresh and hardened properties of concrete.

The performance of slag in concrete, for instance, is made complex due to the complexity of various minerals such as merwinite, calcite and melitite. In addition, there are various processes that occur such as absorption, ion exchange, dissolution and hydrolysis reactions that may influence the chemical and physical properties (Claisse, et al., 2011).

Indeed, the variety of intrinsic (chemical and physical characteristics of the material) and extrinsic factors (such as mix design and curing techniques) are all important in affecting the performance of concrete (Helmuth, 1987).

The mineralogy of cement affects the strength development. C_3S and C_2S constituents both contribute to strength and are both formed during the manufacture of cement at temperatures greater than 800°C though C_3S requires a greater degree of heat to form. Early strength development is attributed to the hydration of C_3S whereas the continued strength over time arises in part due to the hydration of C_2S which may take several years to hydrate (Jäglid et al 2009).

The crystallography of the minerals is another aspect that shows the complex nature of cement. For instance, C_3S can be associated with six different forms of which, the monoclinic and trigonal forms are typical. In C_2S, there can be beta and gamma forms (Greensmith, 2006).

The hydration of C_3S and C_2S involves the compound combining with water to form CSH gel and releases hydroxyl ions (OH^-). The release of hydroxyl ions contributes much to the high pH of concrete and values greater than 12 can be measured. With continued hydration, the CSH gel augments itself, become thicker. Consequently, the formation of further layers of CSH slows down the production of CSH as it makes it more laborious for water to reach un-hydrated grains of cement (Islam, 2005).

2.6. Closure

There are a wide range of aspects which affect the performance of cements. From the literature review, the following may be gathered in general:

Cements have to be economical, meet basic requirements for the user to work with and maintain functionality over its design life.

Economic factors govern the choice of raw materials used in the manufacture of cements. Basic requirements such as setting times and workability affect the presence of mineral additives. The functionality aspect of cement introduces a body of literature relating to ensuring that cement is durable and achieves design strengths.

Hydration studies that pertain to the climatic influences affecting concrete such as ambient temperatures and humidity levels also has a bearing in the performance of cements so that cements achieve their designed strengths and durability's.

The use of modern (such as XRF) and simple techniques (such as the pycnometers) paves a way towards studying the properties of cements and enhancing our understanding of the material.

In conclusion, there are a great number of factors that affect the performance of cements. Optimisation must consider the properties affecting the performance in a holistic way that meets the technical and functional requirements cements are expected to perform.

3. Chapter Three: Research Methodology

This Chapter is separated into five parts.

Part one deals with general aspects pertaining to the study such as the cements involved.

Part two explains the procedures followed to determine the chemical quantities such as sulphates, chlorides and insoluble residue.

Part three details the methodology adopted to prepare specimens for the physical tests pertaining to the study such as cement characteristic strength, cement setting times, loss on ignition and specific surface area.

Part four deals with the concrete portion of the study and outlines the approach used to test specimens for compressive and flexural strength as well as for durability.

Part five describes the procedure followed for preparing the pycnometers and specimens for x-ray fluorescent analysis.

3.1. Part 1: General Aspects

3.1.1. Description of cements

SANS 50197-1 (2000:14-5) provides a means for classifying different cements according to composition and grade of strength. There are five different types of cements according to the classification system, namely:

1. CEM I: Portland cement
2. CEM II: Portland composite cement
3. CEM III: Blast furnace cement
4. CEM IV: Pozzolanic cement
5. CEM V: Composite cement

Each of the five cements can be manufactured to three different strength classes. The three classes of strength are class 32.5, class 42.5 and class 52.5. The class of the cement indicates the strength that may be achieved after allowing for twenty eight days of hydration.

SANS 50197-1 (2000) provides a system of notation that is useful in describing the composition of a particular cement. In relation to the cements in this study, the relevant

notation for Blast Furnace Slag is associated with an ‘S’ symbol, Silicious Fly Ash is allotted a ‘V’ symbol and a ‘L’ symbol is appointed to depict cements containing Limestone.

Furthermore, alphabets ‘A’ and ‘B’ are used to indicate the quantity of extender which the cements contain. As an example, in the case of Blast Furnace cement, an ‘A’ would indicate that the cement contains between thirty five to sixty five percent Blast Furnace Slag. Composite cements are associated with an ‘A’ symbol alongside with a ‘M’ symbol. The notation is used to indicate that there are a number of extenders (such as fly ash, blast furnace slag, silica fume etc.) in the cement and the quantity ranges between six and twenty percent.

The classification system for strength attainment stipulates is encapsulated in Figure 3.1.1—1 Minimum strength requirements are specified for different periods depending upon the type of cement. For instance, a grade 32.5N cement does not have to achieve any minimum strength after 2 days but would have to achieve at least 16Mpa after 7 days and between 32.5 and 52.5 MPa after 28 days of curing. Grades 32.5R, 42.5N&R as well as 52.5N&R have imposed minimum early and late strength requirements at 2 and 28 days but no minimum strength requirements at 7 days.

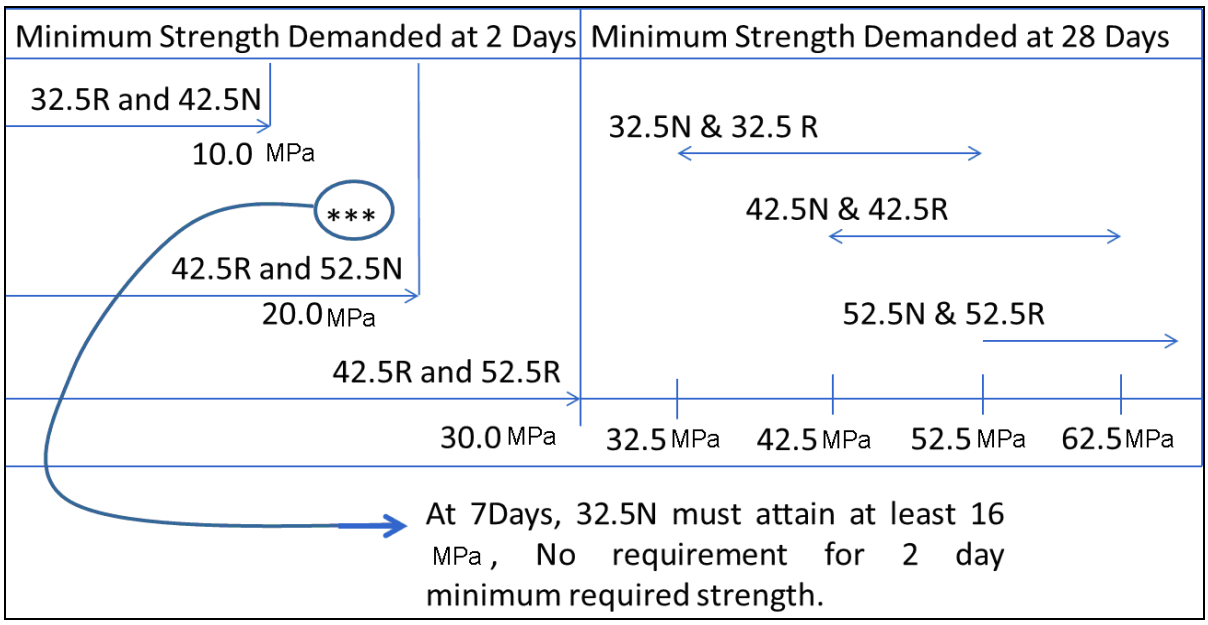


Figure 3.1.1—1: Range of minimum strengths for Different Grades of Cements (Adopted from SANS50197-1 (200:15))

As can be noticed from Figure 3.1.1—1, there is an overlap in minimum strength requirements for 32.5R and 42.5N cements as well as 42.5R and 52.5N cements in the early periods. To explain further, consider that the minimum required strengths for 32.5R and

42.5N cements at 2days is both 10MPa. Likewise, the minimum required strength for 42.5R and 52.5N cements are both 20MPa.

It would be impossible to classify whether cements belong to either a 32.5 or 42.5 class only on the basis of two day strengths. The code stipulates minimum required strengths at 28days to assists with the classifying of cements based on strengths class but there is still overlap in the ranges of strength required at 28 days.

A 32.5R cement for instance would have to have a 28days strength of at least 32.5MPa but no more than 52.5 MPa. Similarly, a 42.5N cement would have to have a 28 day strength of 42.5MPa but no more than 62.5MPa.It should be clear that there is possible overlap in the ranges of strength for the requirement at 28days. If, for example, a 32.5R and 42.5N cement was found to meet the minimum two day strength of 10 MPa and found to have a twenty eight day strength greater than 42.5MPa (but less than 52.5MPa). It could be concluded then that it would be impossible to distinguish the two cements solely on the basis of strength results.

Following the same argument above, a 42.5N cement for example, having a minimum compressive strength at 2days of 20MPa and 28days strength between 42.5 and 62.5MPa could just as well be classified as a 42.5R cement.

Examples of the referencing system follow: A CEM I 42.5N would indicate ordinary Portland cement of class 42.5 with normal hydrating properties. A CEMI II /B-M (S-V) 42.5 R would indicate a cement belonging to the category of composite cements that is of grade 42.5 which has rapid strength gaining properties and between 21 to 35% of slag and siliceous fly ash. Unfortunately, the system does not specify in what proportions the different mineral admixtures might be present in.

3.2. Part 2: Chemical Tests

Internal laboratory procedures from a private laboratory were used for all the chemical tests. The methodology adopted by the private laboratory (name withheld for confidentiality reasons) is based on SANS 50197-1 (2000) standards. The chemical tests conducted were to determine the content of sulphate, insoluble residue and chloride contents. An outline of the methodology is provided herein.

3.2.1. Sulphate

A small quantity of material (1+/-0.0005g) was weighed into a 250 ml cylinder. Deionised water was added followed by 10ml of concentrated hydrochloric acid and vigorous stirring to dissolve the cement which Figure 3.2.1—1 illustrates.



Figure 3.2.1—1: Illustration of Vigorous stirring to Dissolve Cement

The sample was then left on a hot plate, illustrated in Figure 3.2.1—2, and heated to below boiling point (when the sample appeared to bubble) for fifteen minutes.

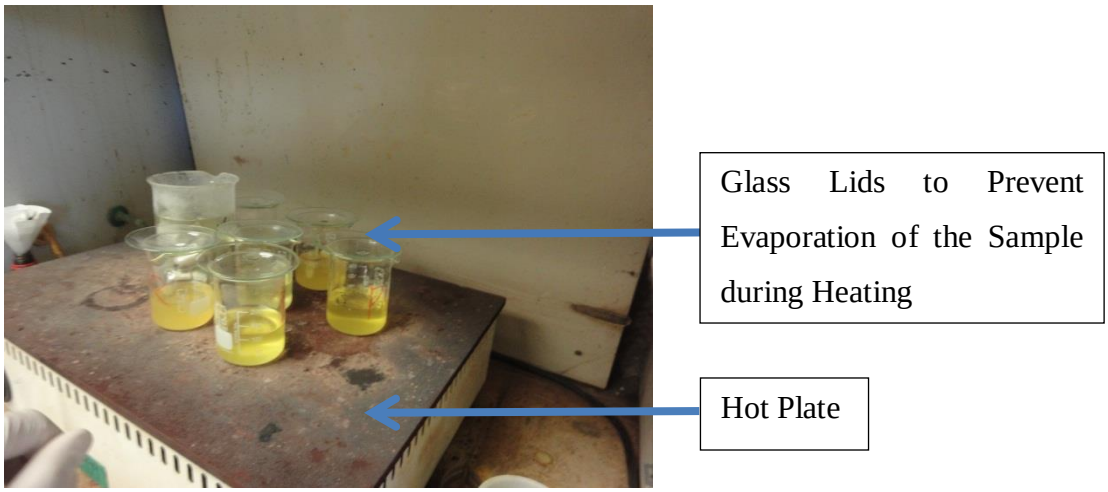


Figure 3.2.1—2: Illustration of Samples Allowed to be heated on Hot Plate

The sample was then filtered through filter paper which is illustrated in Figure 3.2.1—3.

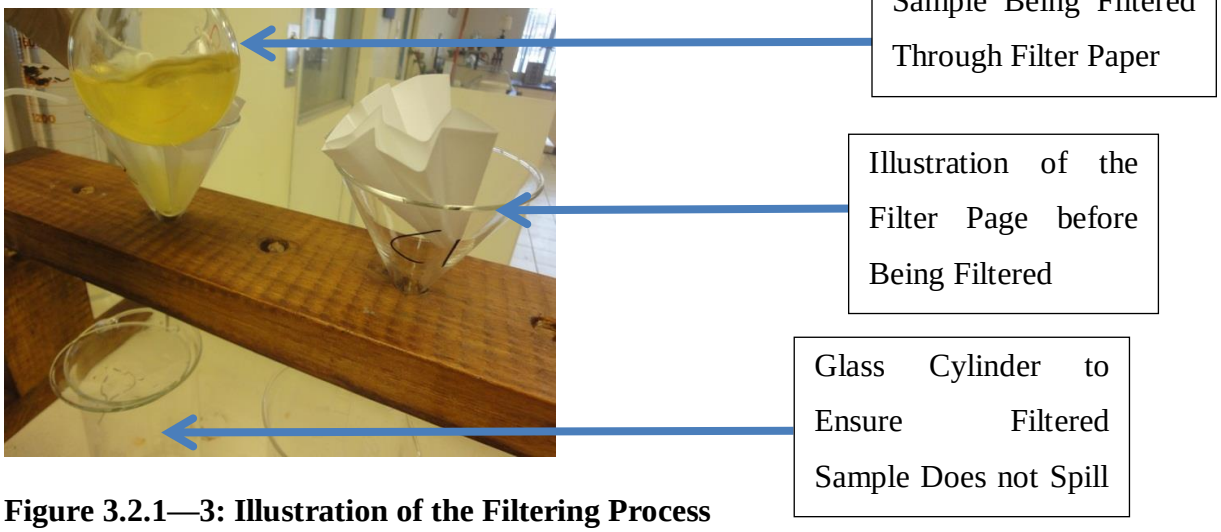


Figure 3.2.1—3: Illustration of the Filtering Process

The Filter paper was then washed several times using a squeeze bottle and containing hot deionised water and is illustrated in Figure 3.2.1—4.

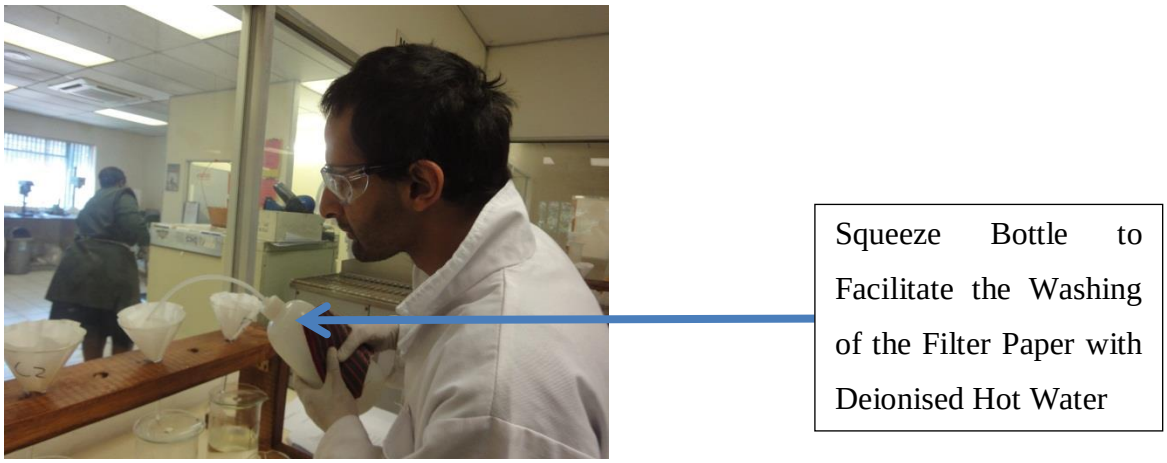
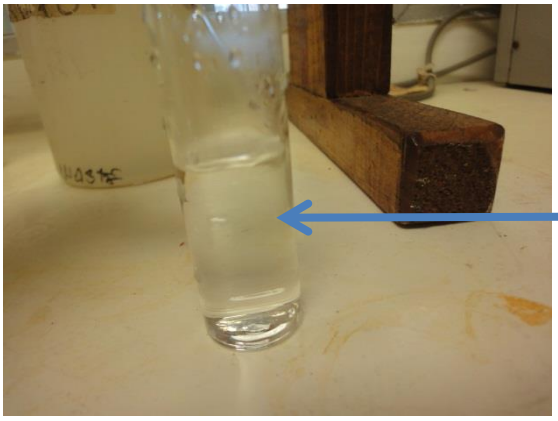


Figure 3.2.1—4: Illustration of the Washing Process

The washing process was continued several times until the water that filtered showed clear turbidity. Clear turbidity was defined as the point after which the sample would be perfectly clear after adding a few drops of silver chloride. This has been illustrated in Figure 3.2.1—5.



A Clear Looking Sample That Does Not Show Any Discoloration or Milkiness after Having

Figure 3.2.1—5: Illustration of a Sample Free of Turbidity

Hot barium chloride was then added to the cylinder and boiled for 30minutes on a hot plate the same way as shown in Figure 3.2.1—2.

The sample was then allowed to stand at room temperature for half an hour. The washing process was repeated until in the same way as was shown in Figure 3.2.1—4. The purpose was to ensure that the sample would be free from chlorides. The use of silver nitrate was used to determine the turbidity.

The sample contained inside the filter paper was rolled and fitted into a crucible which has been illustrated in Figure 3.2.1—6. The crucible together with the sample was then ignited over-night in a furnace at nine hundred and sixty five degree Celsius.

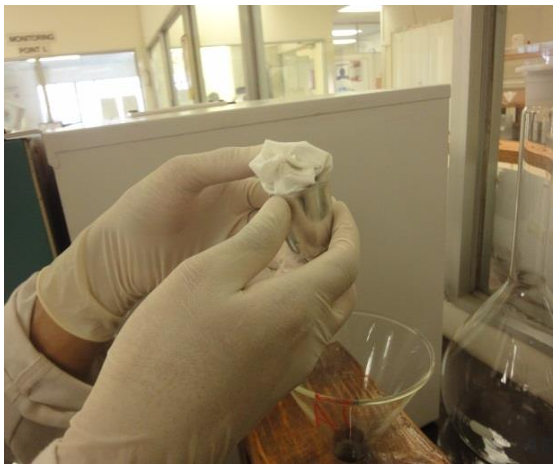


Figure 3.2.1—6: Preparation of Sample for Ignition

An illustration of the furnace has been provided in Figure 3.2.1—7.



Figure 3.2.1—7: Illustration of Sample placed in Furnace

After ignition in the furnace, the crucible was reweighed in order to determine the content of the sulphate of the cement. The equation below was employed to determine the sulphate content:

$$SO_3\% = \frac{Mass\ of\ BaSO_4(g)}{Mass\ of\ Sample\ (g)} \times 34.3$$

3.2.2. Insoluble Residue

The procedure for determining the amount of insoluble residue was similar to the procedure for determining the sulphate content. The initial steps involved weighing out 5 +/- (0.0001) grams of cement in a cylinder. The sample was then digested as was illustrated in Figure 3.2.1—1. After the digestion process, the sample was then assessed for turbidity after rigorous washing as illustrated in Figures 3.2.1—3 to Figure 3.2.1—5

The sample was then treated with five percent sodium carbonate solution and then heated for fifteen minutes on a hot plate. Thereafter, the process of washing was with 200ml hydrochloric acid until the pH was found to be below two. Thereafter, the turbidity was assessed to ensure the colour of the sample was clear. If the turbidity was found to be milky, the washing process was continued.

Lastly, after the washing process, the sample was prepared for ignition the same way as was illustrated in Figures 3.2.1—6 and Figure 3.2.1—7. After the ignition process, the sample was then reweighed. The following equation was employed to determine the insoluble residue content:

$$Insoluble\ Residue\% = \frac{Mass\ of\ Residue\ (g)}{Mass\ of\ Sample\ (g)} \times 100$$

3.2.3. Chloride

This test involved simple titration. First a small quantity of 5+/-0.05g cement was weighed. Thereafter the sample was dissolved in water and nitric acid and heated on a hot plate for fifteen minutes in a similar fashion to the illustrations provided in Figures 3.2.1—1&2.

The sample was then washed through filter paper into a beaker the same way as was shown in Figure 3.2.1—4.

The simple process of titrating was then ensued in order to determine the chloride content as shown in Figure 3.2.3—1 with the end point recorded when the sample turned orange and with type of titrant believed to be NH_4SCN as shown in the equation below.

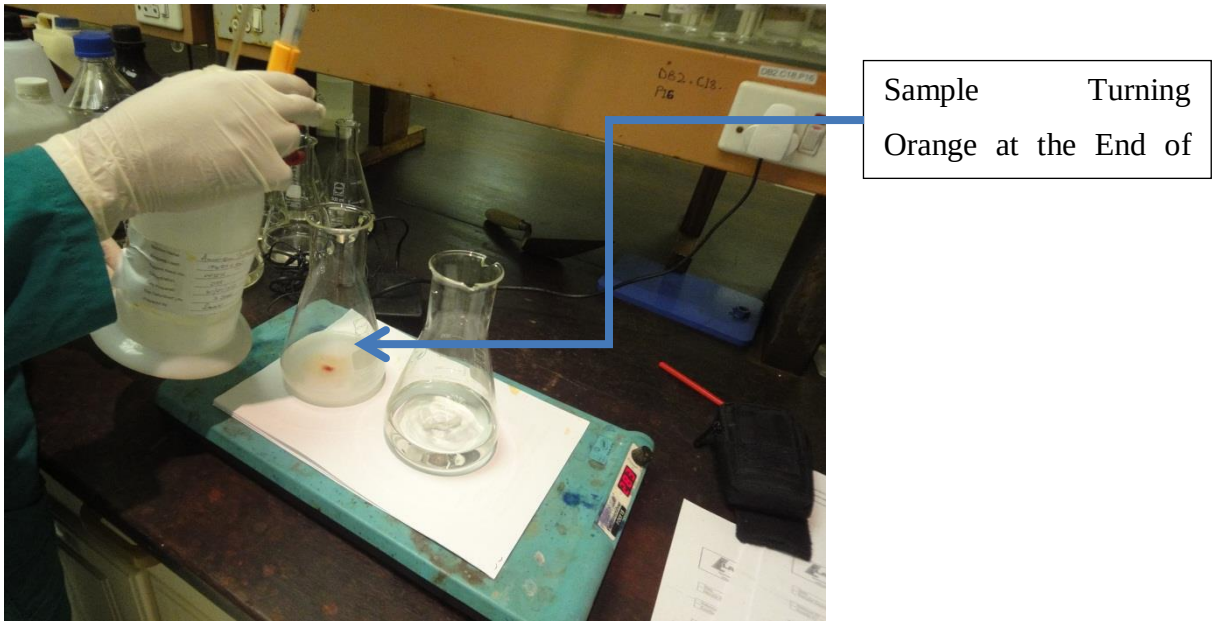


Figure 3.2.3—1: Illustration of a Slight Tinge of Orange marking the end of Titration

The chloride content was determined using the following relationship:

$$\%Cl = 0.1773 * \frac{Titrated\ Volume\ of\ NH4SCN\ (ml)}{Mass\ of\ Sample}$$

3.3. Part 3: Physical Tests

In this section, the methodology employed to determine the cement characteristics strengths, setting times, loss on ignition and specific surface areas are explained.

3.3.1. Cement Characteristic Strength

In order to characterise the strength of the various cements under investigation, prisms were prepared according to the EN 196-1 (2005) standard. Figure 3.1.1—1indicates that though a cement may have a certain class of strength stipulated, the reality is that the strength actually

lies within a certain range. To make clear, it was explained through an example that grade 32.5 cement could have an ultimate strength ranging between 32.5 MPa and 52.5MPa after twenty eight days of hydration. Since this experimental investigation involves comparison of cements, characterising the cement strengths has been conducted.

The basic procedure for determining the cement strengths entails mixing 1350g of standard sand, 500g cement and 250g of water in an electronic mortar mixer. The mixing procedure involves a total of four minutes in which: (a) cement and water are first mixed at low speed for 30 seconds. Thereafter (b), the sand is added to the cement over a period of 30 seconds followed by (c) allowing the contents to mix at high speed for a further 30 seconds at high speed. The sides of the bowl are then (d) scraped to ensure that any dry material clinging to the side walls of the bowl are moistened for 30 seconds. After the scraping of the bowl, (e) a further 60 second delay is stipulated before finally (f) mixing again for a final period of 60 seconds.

The prisms were cured at 23 degrees Celsius and tested at two, seven and twenty eight days for compressive strength by breaking a prism in half and then testing the broken halves for compressive strength. The compressive strength was determined through the following relationship:

$$R_c = \frac{F_t}{1600}$$

Rc represents the characteristic strength in MPa, F_t represents the load in Newton's at failure and the quantity 1600 represents the cross sectional area of the 40mm prisms in millimetres squared. Figure 3.3.1—4 shows the plates used to obtain an applied surface area of 1600mm square since the plate length and breadth is 40mm.

Figures 3.3.1—1 through to Figure 3.3.1—4provides an illustration of the procedure



Figure 3.3.1—1: Specimen on Vibrating Table



Figure 3.3.1—2: Curing of Specimen



Figure 3.3.1—3: Splitting the Prism into Two Approximately Equal Portions (Two Twin Halves obtained)



Figure 3.3.1—4: Twin Halves of Mortar cubes Under Compression

3.3.2. Setting Time

The test for the determination of initial and final setting times involve making use of different sizes of needles to penetrate different depths, from which, the setting times are inferred.

Before any setting times can be conducted, it is necessary to first prepare a mix of standard consistency which is defined as the depth of plunge by a standard 10mm diameter needle penetrating between 4 and 8mm immediately after mixing 500g of cement with an appropriate content of water (196-3, 2005).

An electronic Hobart mortar mixer is employed to mix 500g of cement with different amounts of water until the depth of plunge is found to be between 4 and 8mm. The water and cement are (a) mixed at low speed for 60 seconds followed by (b) scraping the side walls of the bowl to ensure that any dry material is moistened sufficiently. The cement paste is (c) then mixed for a further 90 seconds and thereafter (d) filled in a circular truncated mould of depth 40mm and internal diameter of at least 75mm. The paste is then (e) compacted by jolting the mould walls with the palm of the hand (EN 196-3, 2005).

The size of the needle for initial setting time is 1.13mm in diameter from which the initial set is taken to be the time it takes for the needle to penetrate between 3 and 9mm for cement paste. The final set is taken to be the time that it takes before which a 5mm diameter needle no longer leaves a mark on the surface of the cement paste (EN 196-3, 2005). Figure 3.3.2—1 provides an illustrations of the Vicat apparatus.

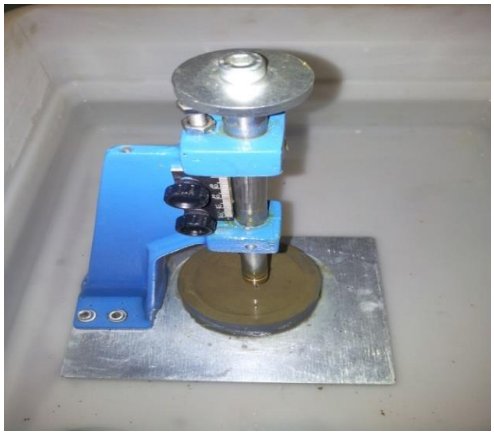


Figure 3.3.2—1: Illustration of Vicat Apparatus.

3.3.3. Loss on Ignition

This is the simplest and quickest test to conduct. A sample of cement is measured and then ignited to 965degrees Celsius as shown in Figure 3.2.1—7.

The difference in weight between the original cement mass and the mass after ignition is indicative of the loss on ignition.

3.3.4. Specific Surface Area

In order to determine the degree of fineness or specific surface area, the density of the cements had to be determined. A Gas Pycnometer was used to determine the densities. The procedure basically involves filling a chamber with cement and allowing air to pass through the chamber after which the density of the cement is estimated.

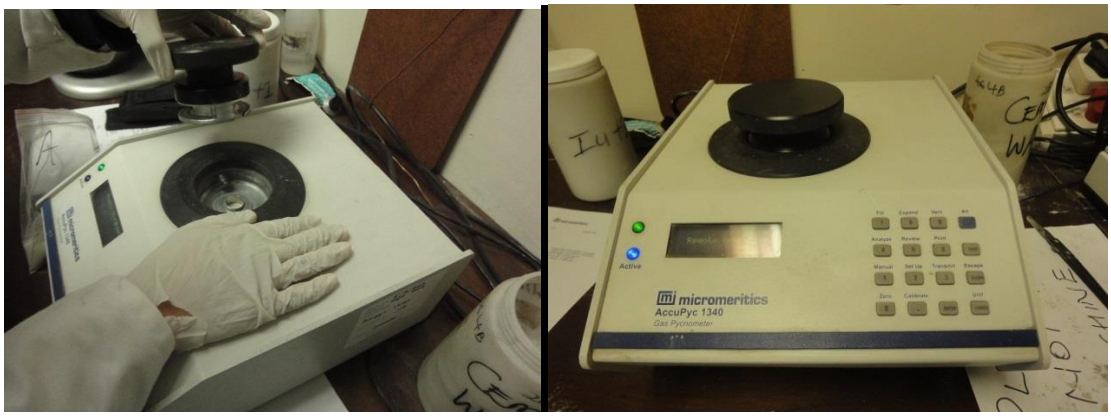


Figure 3.3.4—1: Illustration of the Gas Pycnometer used to infer the Density of the Cements

The Blaine apparatus provided an indication of the specific surface area of the cements. The basic process, as detailed by SABS (1971) involved filling a bed of cement in a chamber as shown in Figure 3.3.4—2, allowing air to be passed through the chamber of the blaine

apparatus as shown in Figure 3.3.4—3 and then measuring the time it takes for water levels to pass certain markings as shown in Figure 3.3.4—3 after which the specific surface area is then inferred.



Figure 3.3.4—2: Illustration of the Bed of Cement in the Chamber of the Blaine Apparatus

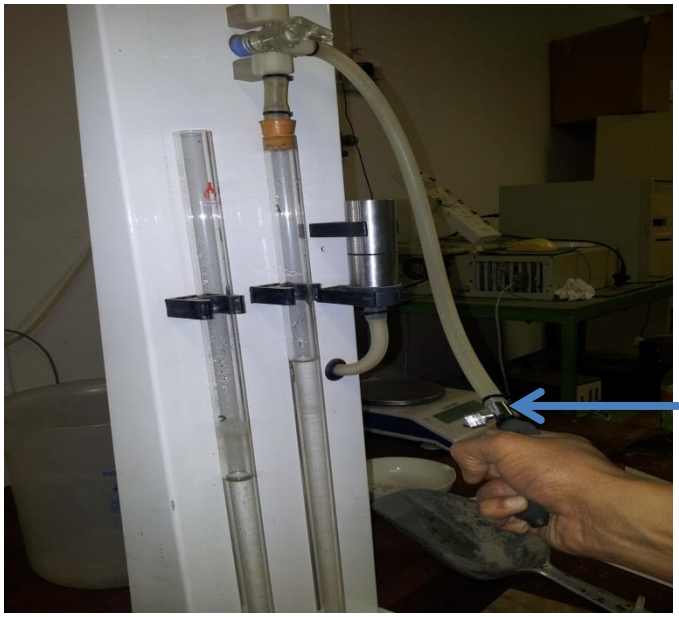


Figure 3.3.4—3: illustration of the Operator Asing a Hand pump to Pass air into the Blaine Apparatus

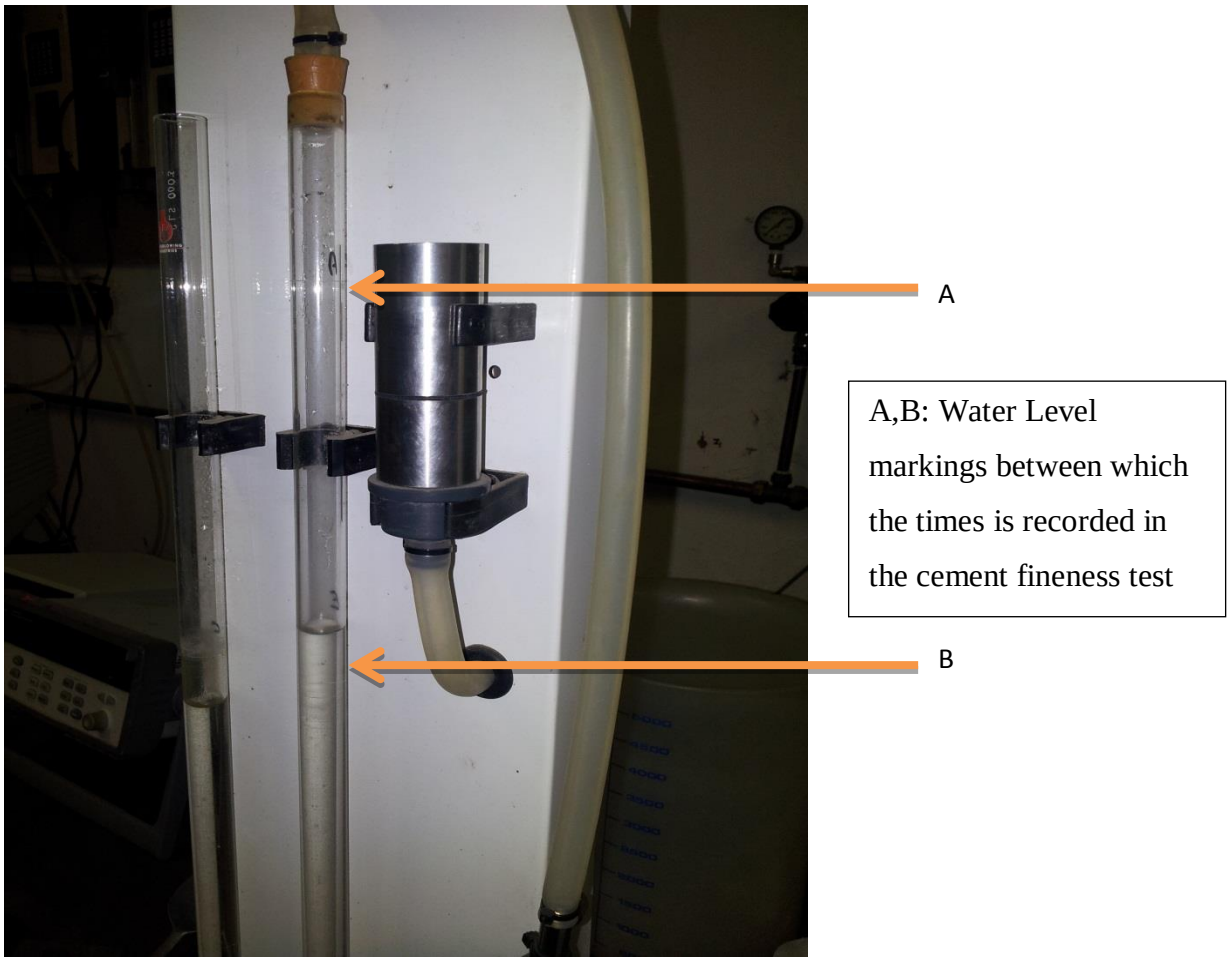


Figure 3.3.4—4: Blaine apparatus for Specific Surface Area Test

3.4. Part 4: Hydration Studies

Details on the preparation of cube specimens for compressive strength, disk specimens for sorptivity and tile specimens to assess the effect of specimen thickness in relation to curing regime is presented.

3.4.1. Concrete Samples: Making Specimens and Determining the Workability

Concrete mixes comprising a water to cement ratio of 0.5 by weight, one part cement to two and a half parts sand and two and a half parts stone by volume were investigated for compressive strength and sorptivity. Andesite sand and stone was used. The stone size was 22mm. The compressive strengths were determined after four, eight and twenty nine days of curing in air, water and in the solar chamber through the following relationship:

$$R_c = \frac{F}{A}$$

Rc represents the compressive strength in MPa, F represents the load recorded at failure and A the cross sectional area of the cube taken to be 100mm^2.

The basic procedure for making of the specimens involved (a) addition of the sand, stone and cement in the concrete mixer and allowing for 60seconds for homogenising the mix. Thereafter, (b) pouring the water into the mixer over a period of 60 seconds and finally (c) allowing the contents to mix for a further 60 seconds.

A slump test was (d) performed by tamping 25times the material filled in three parts until the cone was full and measuring the drop in height of the material after removing the cone. The contents were then (e) loosely filled into 100mm cubes and vibrated for 25+/-5 seconds.

A day after making the cubes, the samples were (f) then de-moulded and (g) cured in one of the three curing regimes (water, air or the solar chamber) for the desired period until the date of crushing.

The samples for sorptivity testing were (a) allowed to cure for 29 days after which, (b) 5mm of the surface faced. Cores were taken (c) from the cubes using a diamond drill. The cores were then (d) cut into thicknesses of 30mm and (e) oven dried at 100C until all moisture was removed (Ikotun, 2009; Arwui, et al., 2011)

3.4.2. Sorptivity

Sorptivity testing involved (a) recording the increasing mass of the disks exposed to a solution of calcium hydroxide. The masses were recorded after (b) 3, 5, 7, 9, 12, 16, 20 and 25 minutes followed by completely saturating the disks for a period of 18 hours in a calcium hydroxide (taken from Ikotun, 2009 which is adapted from Ballim and Alexander (2005)).

The procedure for saturation required that the air inside a desiccator be made into a vacuum by (c) allowing a vacuum generator to suck out air from the desiccator for 3 hours. Water was then (d) allowed to fill up the desiccator after which (e) a further hour of vacuum saturation was prescribed before (f) the samples could be allowed to be completely saturated for the 18 hour period (taken from Ikotun, 2009 which is adapted from Ballim and Alexander (2005)). The relationship used to determine the sorptivity is given by the following:

$$S = \frac{F \times d}{M_{sv} - M_{so}}$$

'S' represents the sorptivity. Symbol 'F' is the slope obtained from plotting a graph of the change in mass of the disks over the twenty five minute period discussed above but with the times in $mm/hr^{0.5}$ of hours square rooted. The portion 'd' is the thickness of the samples recorded to the nearest 0.02mm. Symbol M_{sv} is the mass of the disks after allowing for 18

hours of vacuum saturation and M_{so} is the original mass of the disk after allowing for oven drying. Both M_{sv} and M_{so} are recorded to the nearest 0.01g.

3.5. Part 5: Pycnometer Studies

In this section, two tests were conducted. The first dealt with the water absorption characteristics of different fly ash mixes and is herein referred to as water absorption studies. The second item investigated was whether x-ray fluorescence could be employed to determine the hydration characteristics of the specimens studied for water absorption.

3.5.1. Water Absorption Studies

The mix design involved a water to cementitious material ratio of 0.35 by weight and cement to sand ratio of one to one part by weight. The Cementitious material investigated the water absorption characteristics of three cements blended with 0, 15 and 30% fly ash. The three grades of cement were from the same manufacturer and were grades 32.5, 42.5 and 52.5.

Specimen	Mix Details
A	CEM IV/B-V 32,5R
A-0	Control Mix-No Fly ash
A-15	15% Fly Ash
A-30	30% Fly Ash
B	CEM II/A-M (V-L) 42,5N
B-0	Control Mix-No Fly ash
B-15	15% Fly Ash
B-30	30% Fly Ash
C	CEM II/A-V 52,5N
C-0	Control Mix-No Fly ash
C-15	15% Fly Ash
C-30	30% Fly Ash

Table 3.5.1—1: List of Mixes for Pycnometric Study

The procedure employed to prepare the pycnometers for water absorption studies is explained:

The measured quantities of cement fly ash, sand and water (which was sufficient for making two pycnometers) for the respective mixes were determined. For the control mixes, approximately (a) half of the measured quantity was emptied into the mortar mixer first. Thereafter, (b) approximately half of the measured quantity of sand was added. The remaining quantity (c) of cement was then added followed by (d) the remaining quantity of the measured sand. The contents were (e) allowed to mix for a period of one minute in a dry state. In the second minute, (f) the measured quantity of water was added gradually. In the third minute, (g) the contents were allowed to mix in a wet state.

With regards to the fly ash mixes, the same procedure explained above was used with a minor difference in the procedure. The fly ash was added to the cement in the dry state in two approximately equal portions. The first portion was added after adding half of the measured cement and sand and the second portion after adding the other half of the measured cement and sand.

The mortar was then used to (h) fill two pycnometers approximately half way full. Each pycnometer contained approximately 450g of mortar. The specimens were then (i) vibrated from approximately twenty seconds on a vibrating table. Thereafter, (j) the specimens were filled with water gradually taking care not to damage the surface of the mortar. After the specimens were filled to the brim, they were (k) inundated in water before being sealed with the lid containing the graduated pipette in order to ensure that no air bubbles would be present in the glass jars as shown in Figure 3.5.1—2.

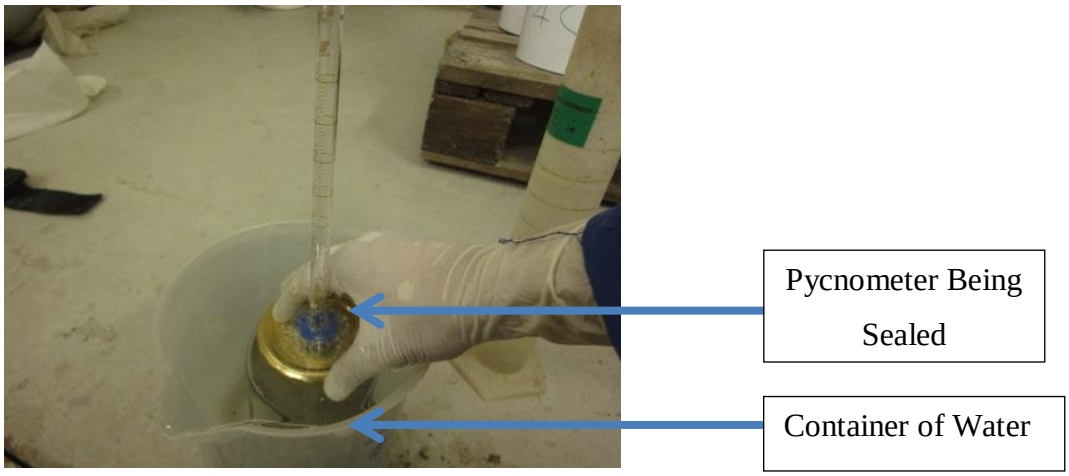


Figure 3.5.1—2: Illustration of Pycnometer Specimen Sealed under Water.

Figure 3.5.1—3 shows a sample of two completed pycnometers. (l) Silicon was used to seal the edges to insure against water leaking from the pycnometers. (m) The water levels were recorded after three, seven and twenty eight days.

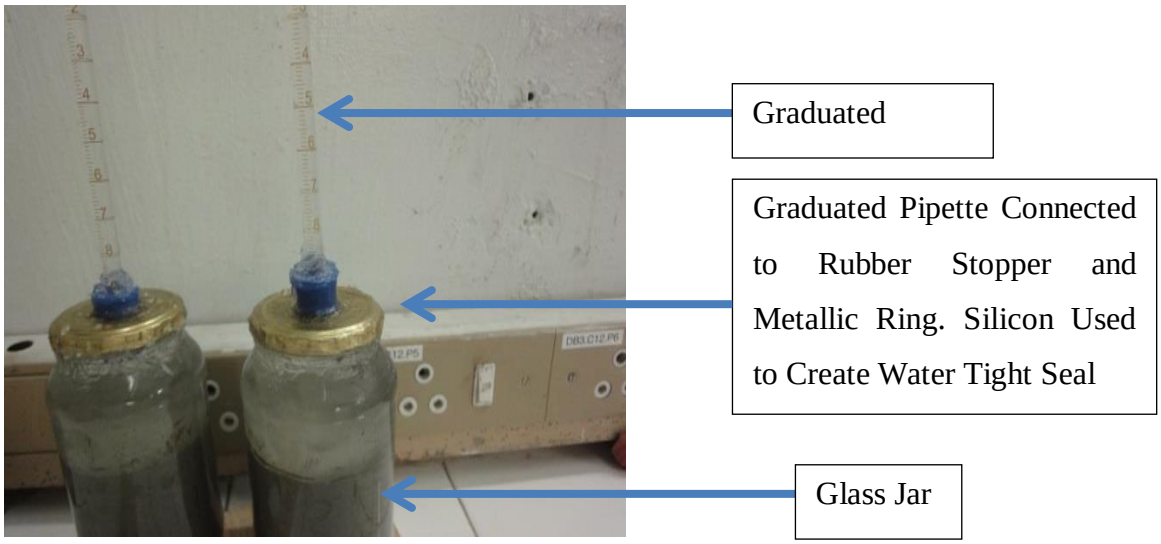


Figure 3.5.1—3: Illustration of Pycnometers.

3.5.2. X-ray Fluorescence (XRF)

XRF was conducted on all of the mixes listed in Table 3.5.1—1. Two types of XRF analysis were conducted. The first was on the mixes in a dry state prior to making cubes and the second was on the mixes after allowing for twenty eight days of hydration. The details are described in a systematic manner.

The first thing that was performed was homogenisation of the sand as it was thought that the XRF test might be sensitive to variations. Thus, the sand was homogenised by continuously shuffling, quartering and mixing the quantities of sand in order to reduce variations that could arise from possibly variable grading of the sand that was purchased or even types of particles that might be present. Figure 3.5.2—1 illustrates the process.



Figure 3.5.2—1: Homogenisation of the sand.

After mechanically homogenising the sand, small samples (500g) were pulverised using an electronic pulveriser as shown in Figure 3.5.2—2 in order to create a fine sand grading as shown in Figure 3.5.2—3.



Figure 3.5.2—2: Electronic Pulveriser



Figure 3.5.2—3: Sand After Pulverising

The mixes listed in Table 3.5.1—1were prepared by predetermined quantities of sand, cement and fly ash. Thereafter, the mixes were further homogenised using an electronic homogeniser shown in Figure 3.5.2—4 which continuously turned and shuffled the mix for ten minutes.

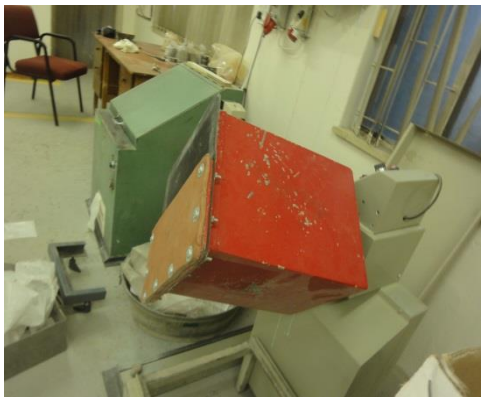


Figure 3.5.2—4: Electronic Homogeniser

The samples were then taken to a swing mill and were ground for 100 seconds as shown in Figure 3.5.2—4. The finely ground sample was then sieved through a number 200 sieve. The sample was a desiccator in the plastic bag up until the day of conducting the XRF test in order to ensure that the sample would not pre-hydrate through absorbing moisture from the atmosphere. A loss on ignition test was conducted on the samples for a period of one hour prior to testing for XRF. The XRF test involved making a bead for each mix before radiating the sample with x-rays to determine the elemental composition of the mixes.

The pulverised cubes were then homogenised using an electronic homogeniser through essentially shuffling and turning the pulverised cubes through revolving for 5minutes. The pulveriser was thoroughly cleaned with a vacuum pump each time so as to remove any dust or debris.

The above procedure was modified to determine the characteristics XRF results on the mixes listed in Table 3.1 after allowing for twenty eight days of hydration. Mortar cubes were made and allowed to cure for twenty eight days in water at twenty two degrees Celsius. Pieces were randomly selected from the centre of the cube through breaking the cube with a hammer.

The fractured pieces selected from the cube were then dried at 100 degrees Celsius for one week in order to remove moisture than may have been present. It was assumed that the temperature would affect all the samples in the same manner should there have been any influence of the selected temperature on drying the samples e.g. on promoting certain hydration reactions. Thereafter, the broken pieces were pulverised into a fine powder the same way as shown in Figure 3.5.2—3. The pulverised samples were then sent to be ground

further in a swing mill. The finely ground powdered form of the cubes were then sieved through a number 200 sieve before testing for loss on ignition and preparing a bead for x-ray fluorescence.

4. Chapter Four: Results and Discussion

A general discussion on the cements in the study is presented in Part one.

The chemical tests conducted for sulphate, insoluble residue and chloride contents are discussed in Part Two.

Part Three expands on the investigation into the characteristic cement strengths, setting times, loss on ignition and specific surface area tests.

Part Four encompasses the studies from the different curing regimes. This section of the report discusses the concrete strength, durability as well as the results from the study on tiles.

The chapter concludes with the results from the examination of the Pycnometric and XRF tests in Part five.

4.1. Part One: Cement Details

A description of the cements is presented following the elemental composition of the cements.

4.1.1. Description of cements in study

Table 4.1.1—1 documents the different class 32.5 cements in the study.

Code	Notation	Description
A1	CEM IV/B-V 32,5N	Pozzolanic Cement. Class 32.5. Normal strength gaining properties. Pozzolanic. Between 21-35% Fly Ash
A2	CEM IV/B-V 32,5R	Pozzolanic Cement. Class 32.5. Rapid strength gaining properties. Pozzolanic. Between 21- 35% Fly Ash

B	CEM V/A (S-V) 32.5N	Composite Cement. Class 32.5. Normal strength gaining properties. Between 6- 20% Fly Ash and Slag
C	CEM III A 32.5N	Blast Furnace Cement. Class 32.5. Normal strength gaining properties. Between 36-65% Slag

Table 4.1.1—1: Documentation of the Class 32.5 Cements in the Study

Four types of class 32.5 cements were considered in the study. Cements A1 and A2 were pozzolanic cements containing fly ash. Cement B was a composite of fly ash and blast furnace slag whereas cement C was a blast furnace cement.

The class 42.5 cements in the study are presented in Table 4.1.1—2.

Code	Notation	Description
D1	CEM II/A-M (V-L) 42,5N	Portland Composite Cement. Class 42.5. Normal strength gaining properties. Between 6-20% Fly Ash and Limestone.
D2	CEM II A-M (V-L) 42.5R	Portland Composite Cement. Class 42.5. Rapid strength gaining properties. Between 6-20% Fly Ash and Limestone.
E	CEM II B/M (S-V) 42.5N	Portland Composite Cement. Class 42.5.

		Normal strength gaining properties. Between 21-35% Fly Ash and Slag.
F1	CEM I 42.5N	Portland Cement. Origin: Pakistan Class 42.5. Normal strength gaining properties.
F2	CEM I 42.5R	Portland Cement. Origin: Germany Class 42.5. Rapid strength gaining properties.
G	CEM II A-L 42.5N	Portland Limestone Cement. Class 42.5. Normal strength gaining properties. Between 6-20% Limestone.

Table 4.1.1—2: Documentation of the Class 42.5 Cements in the Study

In total, six class 42.5 cements were investigated. From the six cements, two were plain Portland cements (F1 and F2); one was a Portland limestone cement (G) whereas the other three cements were Portland composite cements (D1, D2 and E).

The class 52.5 cements in the study are presented in Table 4.1.1—3.

Code	Notation	Description
H1	CEM I 52.5N	Portland Cement. Class 52.5. Normal strength gaining properties.
H2	CEM I 52.5R	Portland Cement. Class 52.5. Rapid strength gaining properties.

I	CEM II/A-V 52,5N	Portland Composite Cement. Class 52.5. Normal strength gaining properties. Between 6-20% Fly Ash.

Table 4.1.1—3: Documentation of the Class 52.5 Cements in the Study

There are three class 52.5 cements. The first two cements, namely cements H1 and H2 did not contain extender content. These were plain Portland cements. The third cement, cement I, was a blended cement containing fly ash.

There are several limitations in this study and it is important to provide an indication of the limitations. For an appreciation of the limitations of the study, the work of Shuttleworth, (1995) is first discussed:

Part of the work of Shuttleworth (1995) involved characterising the fly ashes in her study. Some of the items which Shuttleworth (1995) investigated in order to characterise the performance of the fly ashes included: (a) The minerals present, (b) glass properties (c) particle size and (d) the surface areas of the various fly ashes. The techniques which Shuttleworth (1995) considered included (a) wet chemical analysis, (b) x-ray fluorescence, (c) x-ray diffraction, (d) microscopy and (e) a particle size distribution analyser.

It is now appropriate to outline some of the limitations of this study after gathering a perspective of the approach that Shuttleworth (1995) had followed.

In this study, the source of the cements and location of where the cements were manufactured are not disclosed for confidentiality reasons.

The exact quantity of extender content in the cements was unknown. The mineralogy and geological source of the cement constituents were also unknown. In addition, the types of activators and strength enhancers which the cement manufacturers may have incorporated in the cements were also unknown. Furthermore, the glass properties, particle shape and size were not considered in the study.

It would have added value to the study if the items listed above could have been studied. However, due to the scope and time constraints of the project, it was not possible to conduct such intensive tests on all the cements.

Despite these limitations, it is expected that all the cements would perform satisfactorily in terms of physical and chemical performance. Motivation for this claim is derived from the study of Mushenje (2012). Mushenje (2012) cited that from the study of Graham (2002) that from the many different sources of clinker studied in South Africa, there were significant differences from a crystallographic perspective but despite these differences, the clinkers were suitable for cement manufacture.

4.1.2. Cement Oxides

An XRF analysis of the cements is presented in this section. This analysis provides an indication of the elemental composition of the cements.

The oxide analysis of the cements is separated into five parts. The First Part presents the four major oxides present in Portland cement. In Parts Two to Five, the Sulphur oxide, Magnesium oxide, Alkali quantities and thereafter the Trace elements are presented.

The actual oxide results did not summate to 100 percent. It was decided that all the oxide results should be normalised to one hundred percent so that the results could be interpreted with greater accuracy.

Appendix 1 contains the XRF results on the cements analysed.

4.1.2.1. Four main Oxides of the Cements

The four major oxides required for the manufacture of Portland cement are Calcium oxide, Silicon oxide, Aluminium oxide and Iron oxide (Addis, 2008).

The typical ranges of the oxides required in clinker for the manufacture of Portland cement is presented in the figures that follow. This is done so that an indication of the extent to which these oxides are present in the various cements can be appreciated.

Figure 4.1.2.1—1 presents the Iron oxide contents for all three classes of cements.

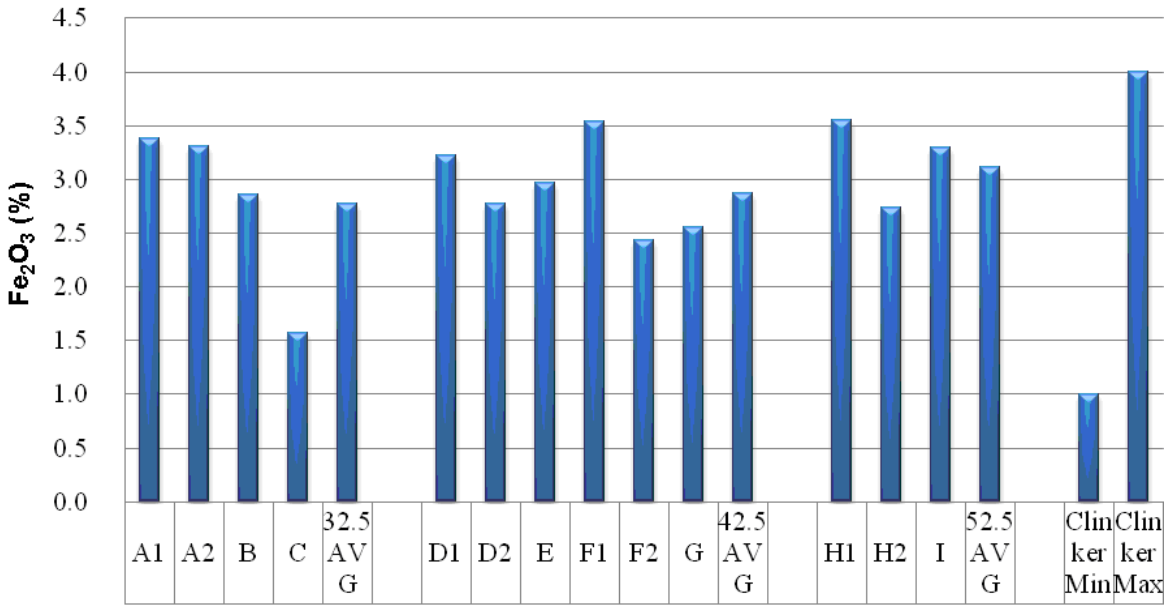


Figure 4.1.2.1—1: Iron Oxide Content of the Cements

It is evident that the quantity of Iron oxide in all the cements are within the typical range of 1-4% required to manufacture Portland cement as suggested by Addis (2008).

Figure 4.1.2.1—2 shows the Aluminium oxide content of the cements.

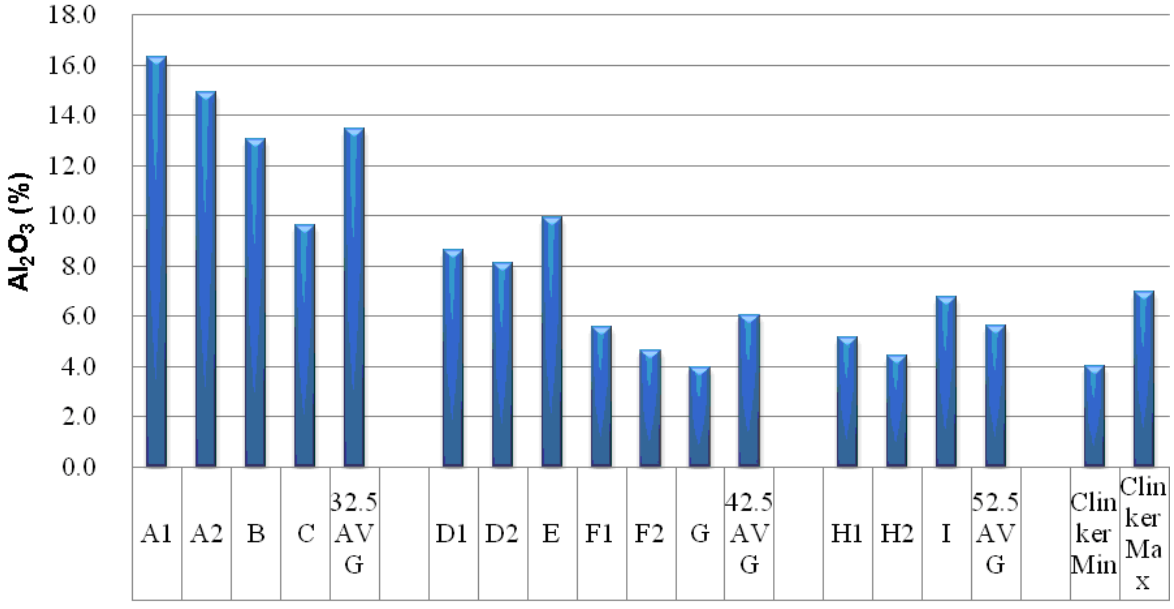


Figure 4.1.2.1—2: Aluminium Oxide Content of the Cements

It is clear that plain Portland cements, namely cements F1, F2, H1 and H2 have an Aluminium oxide content which is within the typical range of 4-7% required to manufacture Portland cement as suggested by Addis (2008).

The quantity of Aluminium oxide present in cement G is within the 4-7% range. Cement G is a limestone containing cement.

Cement I (containing fly ash ranging between 6-20%) contains 6.7% Aluminium oxide and nearly exceeds the upper limit of 7% which Addis (2008) suggests in clinker for the manufacture of Portland cement.

Besides the six cements discussed above, all the other cements exceed the 7% Aluminium oxide required for the manufacture of plain Portland cement. The finding of high Aluminium content for all these cements suggests that the fly ash and slag used in the manufacture of these cements may have been much more Aluminous in nature than the clinker.

Figure 4.1.2.1—3 shows that Silicon oxide content of the cements.

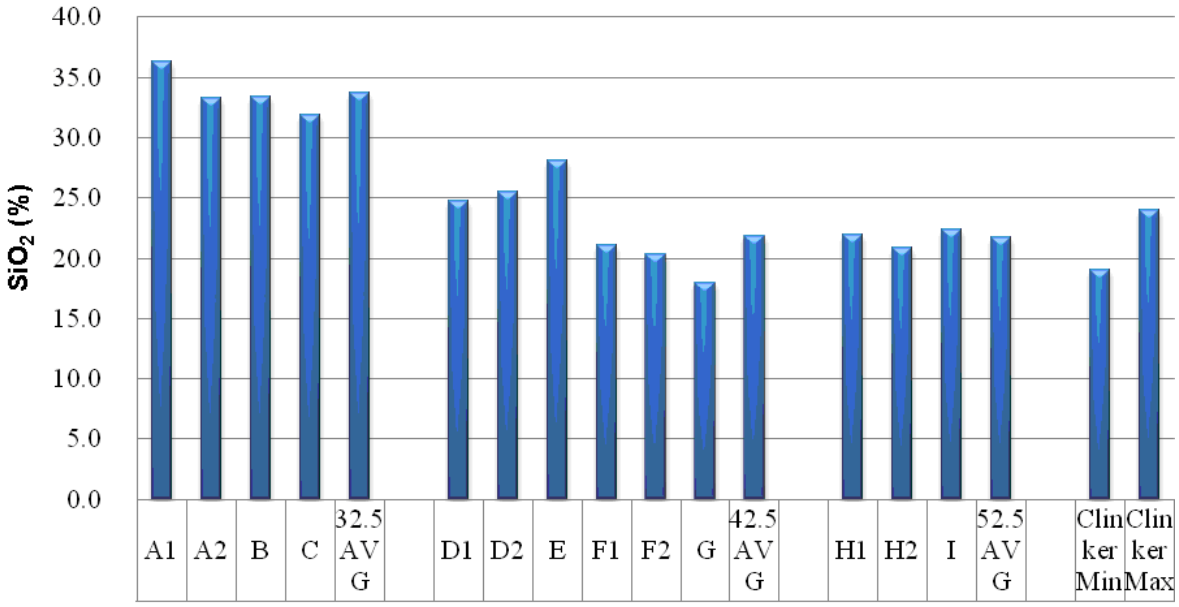


Figure 4.1.2.1—3: Silicon Oxide Content of the Cements

From Addis (2008), the typical content of Silicon oxide for the manufacture of plain Portland cement is 19-24%. The plain Portland cements in the study, namely cements F1, F2, H1 and H2 are all found to have Silicon oxide contents within this range.

With regards to the class 42.5 cements, the Silicon oxide content of cement D2 and E exceed the upper threshold of 24%.

With regards to the class 32.5 cements, the silicon dioxide contents of all the cements are exceeded.

Most of the fly ash and blast furnace cements have high Silicon oxide contents (cements A1, A2, B, C and E). The limestone containing cements (cements D1, D2 and G) appear to have low Silicon oxide quantity.

These findings suggest that the fly ash and blast furnace slag extenders may have been silicious in nature as the content of Silicon oxide registered is found to be greater than the range which Addis (2008) prescribed for the manufacture of plain Portland cements.

Figure 4.1.2.1—4 shows that Calcium oxide content of the cements.

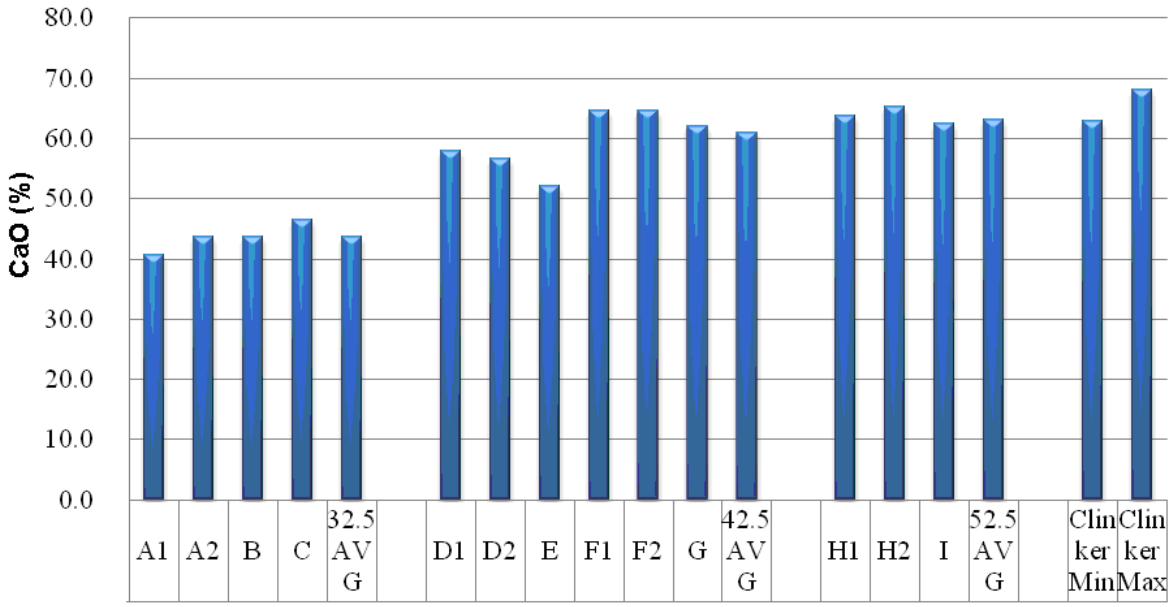


Figure 4.1.2.1—4: Calcium Oxide Content of the Cements

The suggested range of Calcium oxide, according to Addis (2008), for the manufacture of plain Portland cement is 63%-68%.

It is found that the plain Portland cements, namely cements F1, F2, H1 and H2 have Calcium oxide contents that are within the typical range required for the manufacture of plain Portland cement.

Cement G, which contains between six and twenty percent limestone is found to have a Calcium oxide content of 62%. This finding suggests that the limestone blended with the clinker is Calcareous which is in agreement with Hewitt (1998) who mentioned that limestone is calcareous and a valuable source for Calcium oxide in cement manufacture.

Cement E contains fly ash and blast furnace slag and is found to have a low calcium oxide content. This finding suggests that the fly ash and slag used in the manufacture of cement E has low Calcium value compared to the clinker.

Cements D1 and D2 both contain limestone and fly ash. However, cements D1 and D2 are registered to have low Calcium oxide contents. The content of Calcium oxide of these cements is comparable to cement E which contains fly ash and slag and is also a class 42.5 cement. The low Calcium oxide content suggests that cements D1 and D2 contain more fly ash than limestone. If cements D1 and D2 contained more limestone than fly ash, it would be expected that the Calcium oxide content would be higher based on the observation made for cement G.

The class 32.5 cements have the least Calcium oxide content with an average of 43% observed.

The findings suggest that the fly ash and blast furnace extenders used in the manufacture of the cements are not calcareous in that they contain low Calcium oxide.

4.1.2.2. Sulphate Oxide

Figure 4.1.2.2—1 shows the sulphate levels present in the cements.

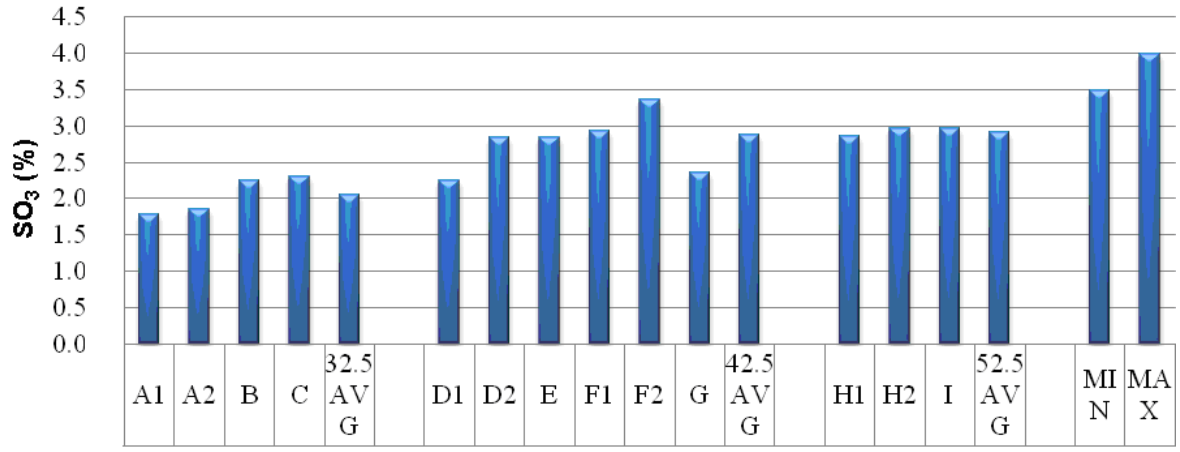


Figure 4.1.2.2—1: Sulphate Oxide Content of the Cements

Typically, sulphate varies between 3.5 and 4% in cement (SANS 50197, 2000) depending on the class and type of cement. All the cements do not exceed the permissible sulphate levels.

On the whole, it was evident that the class 32.5 cements (2% average) had less sulphate present than the class 42.5 cements (2.8% average) and class 52.5 cements (2.9% average). The findings suggest that the class 32.5 cements could offer superior protection against

sulphate attack compared to the class 42.5 and class 52.5 cements since the average Sulphur oxide content was registered to be the least.

4.1.2.3. Magnesium Oxide of the Cements

The magnesium oxide contents of the cements are presented in Figure 4.1.2.3—1.

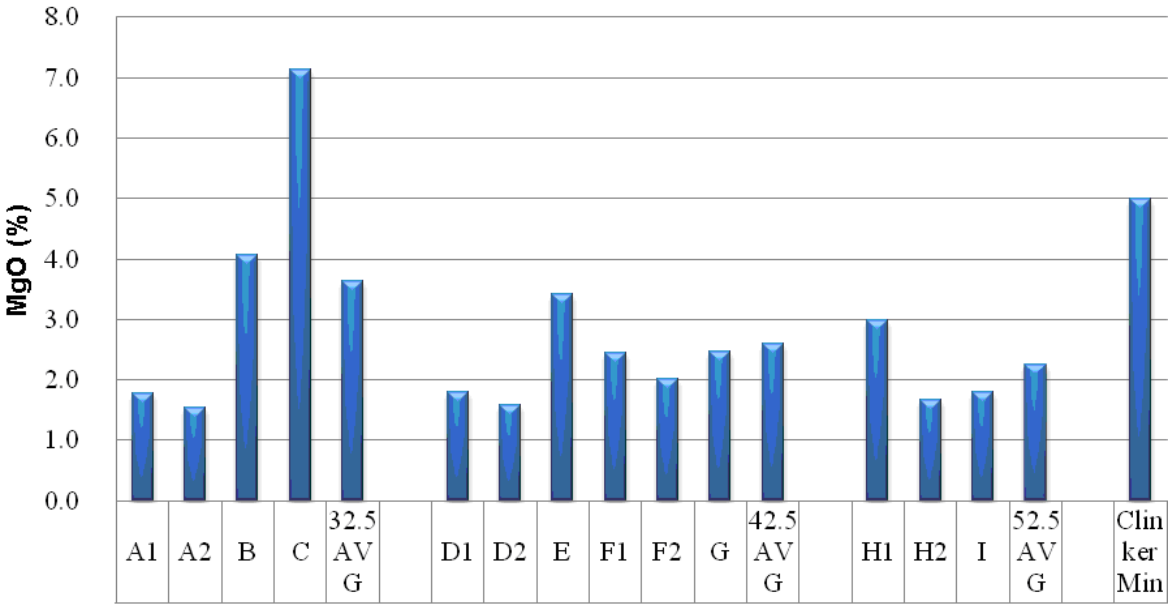


Figure 4.1.2.3—1: Magnesium Oxide Content of the Cements

For an indication (general sense of the cement Magnesium contents) on the Magnesium content of the cements, SANS 50197 (2000) prescribes a limit of 5% for plain Portland cements. All the cements are found to satisfy the general limit for Magnesium oxide except cement C which has a Magnesium content of 7.1%.

Cement C is a blast furnace cement containing between thirty six and sixty five percent slag. There is no minimum or maximum value of Magnesium oxide for cements containing extenders. Thus, cement C can be regarded to be acceptable. The high magnesium content may be associated with the type of slag used in the cement but this speculation would require an XRF analysis of the slag that was blended with the clinker used to manufacture cement C in order to ascertain this.

It should be mentioned that the Magnesium attack can lead to long term durability concerns. However, the mineral type is important to consider. For instance, the periclase type can cause destructiveness in the long term (Long, 1983).

It should also be mentioned that the content of Magnesium oxide in cement can range between three to thirteen percent (Kourounis, et al., 2007).

4.1.2.4. Alkali Contents of the Cements

He & Li (2005) mention that the total equivalent of alkalis, given by the sum of Na_2O (Sodium oxide) and $0.64K_2O$ (Potassium oxide), present in cement range between 0.3-1.5%. Figure 4.1.2.4—1 shows the equivalent alkali content of the various cement.

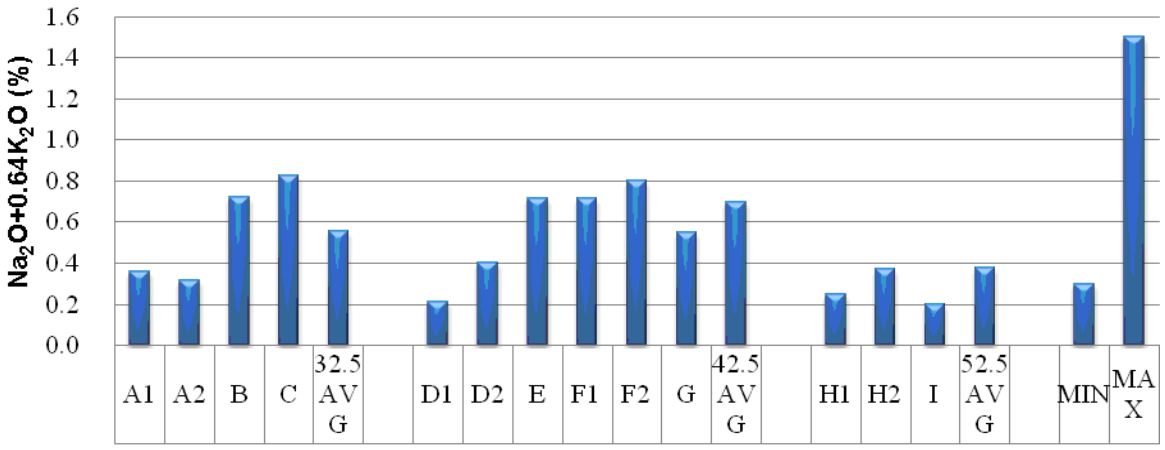


Figure 4.1.2.4—1: Equivalent Alkali Oxide Content of the Cements

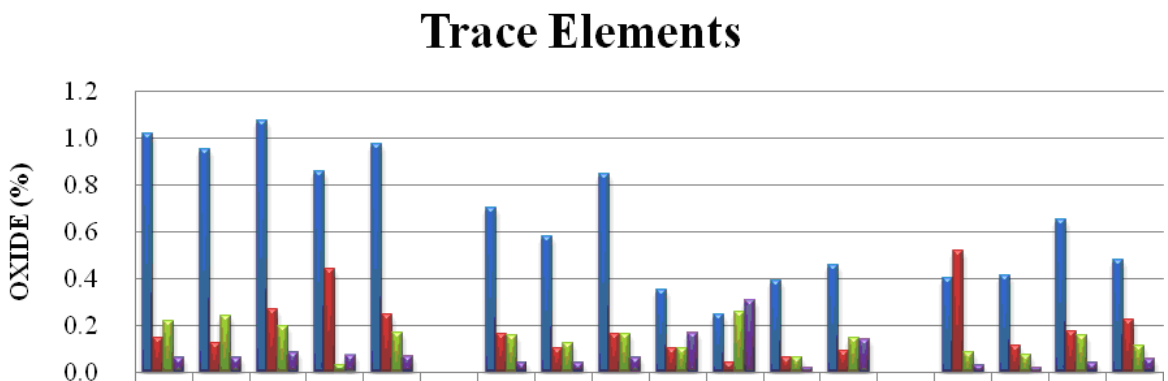
It is noticed that all the cements have a combined alkali content that is within the permissible equivalent Alkali contents suggested by He and Li (2005).

The Alkalis of the plain Portland cements from Germany (F2) and Pakistan (F1) are found to be higher than the local plain Portland cements, namely cements H1 and H2 and so, could be more susceptible to alkali attack.

4.1.2.5. Trace Element Oxides of the Cements

The presence of trace elements, as Lokothwayo (2007) mentions, is widespread and occurs in all ecosystems. Lokothwayo (2007) mentions that trace elements can be found in soil, rock as well as in precipitated forms. There are different processes that contribute to the dispersion of trace elements. Rainfall water is an example which would serve to transport trace elements found in soil and rock to move from one place to another (Lokothwayo, 2007).

Figure 4.1.2.5—1 presents the trace elements present in the various cements. The significance of the proportions of trace elements present if the cements and their influence in concrete are not discussed in this research report and would require further testing.



	A1	A2	B	C	32.5 AVG	D1	D2	E	F1	F2	G	42.5 AVG	H1	H2	I	52.5 AVG
TiO2	1.02	0.95	1.08	0.86	0.98	0.70	0.58	0.85	0.35	0.25	0.39	0.46	0.40	0.41	0.65	0.48
Mn2O3	0.15	0.12	0.27	0.44	0.24	0.17	0.10	0.16	0.10	0.04	0.06	0.09	0.52	0.11	0.18	0.22
P2O5	0.22	0.24	0.20	0.03	0.17	0.16	0.12	0.16	0.10	0.26	0.06	0.15	0.08	0.07	0.16	0.11
SrO	0.06	0.06	0.08	0.07	0.07	0.04	0.04	0.06	0.17	0.31	0.02	0.14	0.03	0.02	0.04	0.06

Figure 4.1.2.5—1: Trace Element Oxides of the Cements

From the four trace elements shown, the presence of Strontium oxide is the least significant. The local cements are recorded to have between 0.02 and 0.07%. The imported cements have a greater percentage with the German cement containing 0.31% and the Pakistani cement containing 0.17%.

The amount of Manganese and Titanium oxide found in the German and Pakistani cements appear to be less compared to the local cements.

Eštoková and Palaščáková (2012) mention that Slovak eco labelling guidelines limit Pentium oxide to no more than three percent. All of the cements are within the limit of three percent.

4.2. Part Two: Chemical Results

In this section of the report, the sulphate, insoluble residue and chloride test results are presented.

For each test, the assumptions and limitations of the study are first presented. Expected outcomes of the test are then presented. These expectations are then compared to the measured results. Possible sources of error as well as the implications of the findings are highlighted.

With regards to the inter-laboratory studies, three results are presented for the reference cement tested from Germany. The results from BAM are ascribed the key word ‘BAM.’ The results from the Participating Laboratories are ascribed the notation ‘PL’. The results of the

samples tested for this research report are recognised with the label ‘F2’. The BAM, PL and F2 results that are presented are derived from BAM (2012).

The results from the locally tested cements are presented and compared to the outcome of BAM results. In comparing the results of F2 and PL, the BAM results are used as a basis for comparison. It is assumed that the results from BAM give a better representation of the properties of the reference cement.

The reason for opting to use the results from BAM instead is probably because BAM results are more accurate compared to the results of all the participating laboratories. It should be borne in mind that BAM was one of the main coordinators and initiators of the inter-laboratory study. It is reasonable to expect that such an important role would probably have the effect that the institution would take great precaution to ensure that their results are accurate as possible.

4.2.1. Sulphate Content

The measured sulphate contents can be found in Appendix 2.1.

4.2.1.1. Assumptions and Limitations

Five cements were selected. The sulphate test was only performed once. Thus, the information drawn from test result gives an indication of the performance of the cement based on a once off test and not on the performance in the long term. It is assumed that the results are representative and accurate of cements manufactured at any period during the year.

The source of sulphates may be derived from the raw materials used to manufacture the cement, any chemical enhancers present in the cement, the gypsum as well as the extenders that may be present. The contribution of the different sources towards the total measured sulphate content is unknown.

This study is limited to investing the internal contents of sulphate in cement and not the performance of the cements used in concrete where sulphated environments are of concern.

4.2.1.2. Expectations

The South African cements were SABS approved. It was expected that all the South African cements would pass the test for sulphate based on the fact that the cements had certification.

The Pakistani cement under investigation was also expected to pass the test for sulphate content as there was no reason to doubt the certification which the cement had.

It was not clear whether the German cement would pass the test for sulphate content as the certification details of the cement were not known. However, it was expected that it would pass the test on the basis that there would be little reason to suppose that the cements were manufactured to deliberately have a high or low sulphate content for the inter-laboratory study. The basis for the speculation is motivated by considering that Germany is a signatory to the EN committee dealing with codes of practice and guidelines that govern the manufacture of cement.

4.2.1.3. Results and Discussion

The results of the sulphate test on the German cement is presented in Figure 4.2.1.3—1 (BAM 2012).

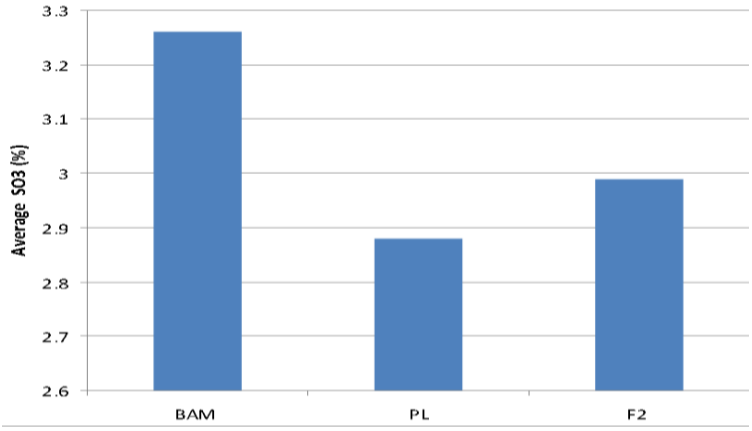


Figure 4.2.1.3—1 Sulphate Content Results for Inter-Laboratory Study on German Cement.

The results obtained from F2 differ by 27% relative to the BAM results. The results from the Participating Laboratories (PL) on average differ by 11.7%.

It can be seen that the percentage differences indicate that the sulphate contents determined by the participating laboratories are more closely related to the BAM results than those determined in this study. However, statistical tools such as a t-test would be necessary to confirm such speculation since the results presented are averages.

It is important to elaborate on the results obtained in the inter-laboratory study. If it is indeed true that the sulphate content determined on the German cement for this study by BAM is incorrect and should have been 27% higher, it would imply that the sulphate contents determined for the Pakistani and local cements are also incorrect.The percentage differences could be attributed to several reasons. There could have been variations in the preparation of

the reagents used in the analysis, the efficiency of the conductor in performing the experiment as well as possible variations in the testing conditions.

The results of the sulphate test for the different cements are presented in Figure 4.2.1.3—2.

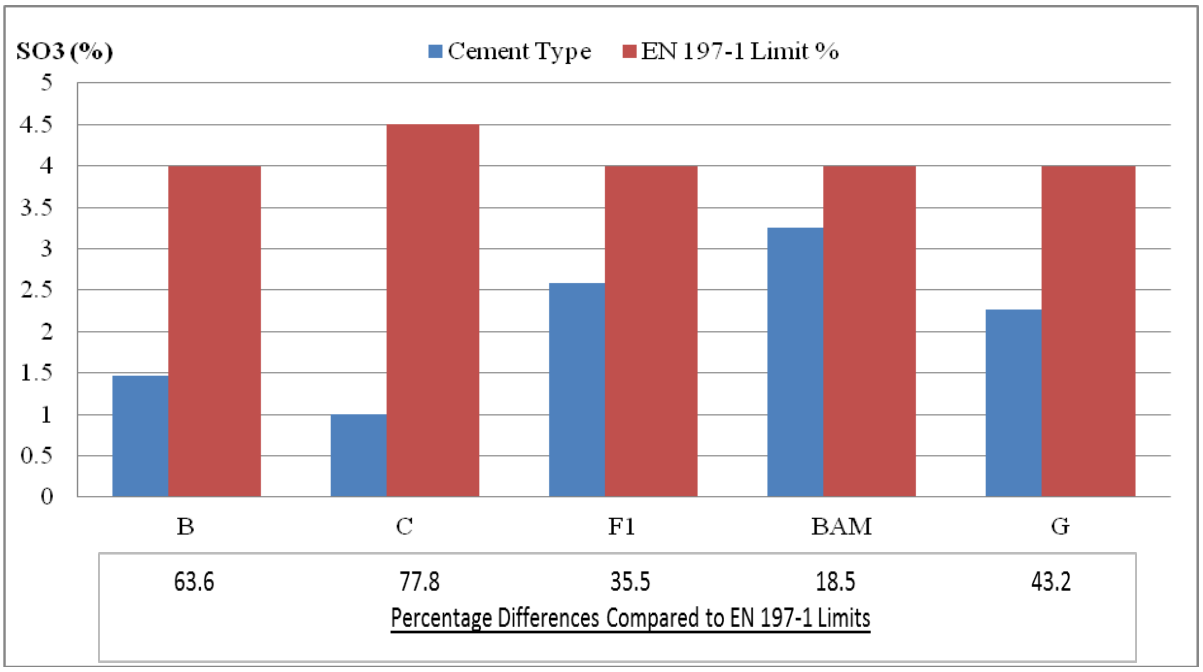


Figure 4.2.1.3—2: Sulphate Content Results for the Different Cements in the Study

EN 196-2 (2005) provides two limits for the sulphate content. The first limit provided is for characteristic sulphate contents of the cements. These limits are considered to be applicable to the manufacturing companies since the limits account for routine testing of the cements.

The second limit provided by EN 196-2 (2005) is considered to be applicable to this research investigation as the limits stipulated are applicable to cements being tested once off.

For all cements, the sulphur contents do not exceed the allowable limit prescribed by SANS 50197 (2000).

Cement C has the lowest content of sulphate and is 77.8% lower than the allowable limit. The German cement using BAM results show that the content of sulphates is close to the allowable limit (18.5%). The Pakistani cement (F2) had the same chemical composition as the German Cement (CEM I 42.5N) but was 35.5% lower than the allowable limit of 4%.

It also appears that the 32.5 cements (C and B) had lower sulphur contents compared with the 42.5 cements (BAM, F1and G). This could possibly be explained through studying the chemical composition of the cements:

Cement B is a composite cement with between six and twenty percent of fly ash and slag. Cement C is a blast furnace cement with between thirty six and sixty five percent slag. BAM and F1 are plain Portland cement containing no extenders. Cement G is a Portland composite cement with between six and twenty percent limestone.

Class 32.5 cements possibly have greater proportions of extenders compared to the 42.5 cements. Incorporating an extender in cement would imply that the prevailing oxide contents of the clinker would get diluted. The greater the amount of extender content incorporated, the greater the dilution effect.

Thus, if the above speculation is correct, it would imply that the extenders have less sulphates compared to the cement clinker and would further imply that the greater the extender present, the less the occurrence of sulphates (due to the dilution effect).

The sulphate contents of cement F2 is 27% lower compared to BAM. The sources of error between the results of BAM and the Participating Laboratories also appear to be large (11.7%).

It was mentioned that the results from the inter-laboratory study revealed that the sulphate content determined on the reference cement in this study did not match the results determined by BAM. The sources of error were also mentioned. It is assumed that the sources of error are consistent for all the sulphate tests. Thus, based on the results obtained and on the assumption that the error associated with the tests are carried through, the sulphate contents for all the cements are within the allowable limits prescribed in SANS 50197 (2000).

4.2.1.4. Implication of Findings

Based on the results obtained and on the assumptions made, the sulphate contents for all the cements are within the allowable limits prescribed in SANS 50197 (2000).

The findings suggest, based on the contents of internal sulphates determined, that class 32.5 cements (B and C) would offer greater resistance to sulphate attack whereas the plain Portland cements (F1 and BAM) offer comparatively less resistance to sulphate attack.

4.2.2. Insoluble Residue

The measured insoluble residue contents can be found in Appendix 2.1.

4.2.2.1. Assumptions and Limitations

The insoluble residue contents were determined for five cements. The insoluble residue test was only performed once. It is assumed that the results are representative and accurate of cements manufactured at any period during the year.

The source of insoluble residue may be derived from the raw materials used to manufacture the cement, any chemical enhancers present in the cement, the gypsum as well as the extenders that may be present. The contribution of the different sources towards the total measured insoluble residue content is unknown.

The experience of the author in trying to determine the insoluble residue content proved to be extremely difficult. Several attempts were made before the insoluble residue content could be estimated. Even after several attempts, it was not possible to obtain the exact insoluble residue content. Thus, the interpretation of the results contains a certain degree of inaccuracy. This poses a limitation on comparing the insoluble residues of the different cements and so, a comparison has been avoided.

The study was limited to analysing insoluble residue contents of the cement in the dry state. The influence of insoluble residue content on strength and durability performance was not investigated. Insoluble residue can have implications on strength and durability as was discussed in the literature review.

4.2.2.2. Expectations

There was particular interest in determining the insoluble residue content of cement B, hence the reason for the four attempts. The intention for wanting to investigate the amount of insoluble residue was two fold. Firstly, to determine possible reasons as to why EN 196-2 (2005) prescribed limits for CEM I and CEM III cements only and no limits for the other types of cements. Secondly, it was decided to test the claim of Abeyruwan et al (2012) which is discussed hereunder:

Abeyruwan et al (2012) tested a fly ash cement and found that the amount of insoluble residue exceeded the allowable limit prescribed in the code of practice used in their study. Abeyruwan et al (2012) explained that even though the insoluble residue content was high, the result would be acceptable since the cement contained fly ash. Abeyruwan et al (2012) had claimed that a fly ash cement would be expected to have a high insoluble residue content.

It was expected that the insoluble residue contents of cement C (a blast furnace cement) and the plain Portland cements (the German and Pakistani cements) would be within the

acceptable limits as there was no reason to doubt the certification which the cements received.

It was expected that the insoluble residue content of cement G, a limestone containing cement, would be within the acceptable limits prescribed by EN 196-2 (2005) even though EN 196-2 (2005) does not prescribe a limit for type II cements.

Motivation for this expectation is drawn from Beddey et al (2013) found that for between zero and thirty five percent of limestone addition to cement, the insoluble residue content altered between 0.66% and 1.56% only.

4.2.2.3. Results and Discussion

The insoluble residue results of the different laboratories (BAM, 2012) follow:

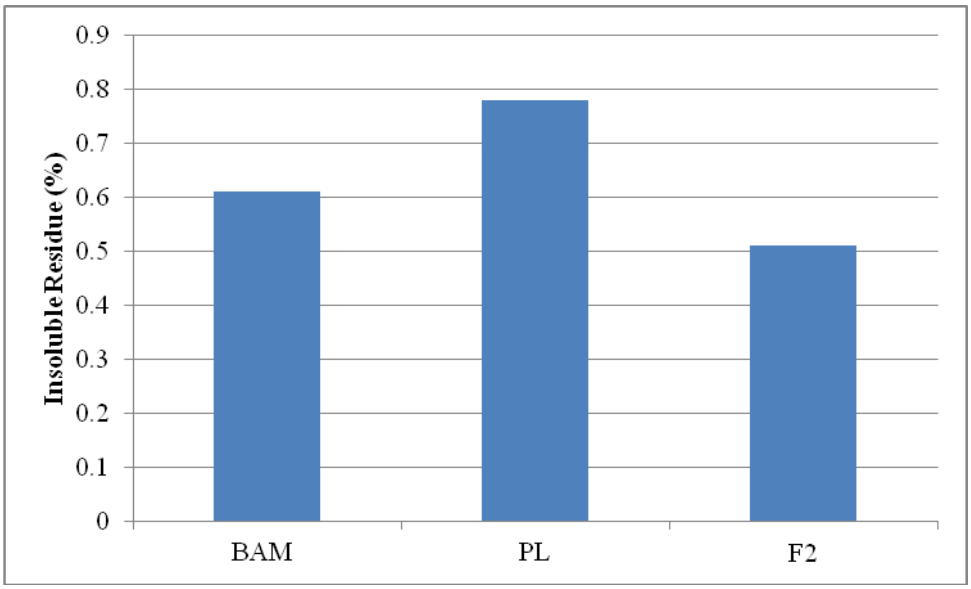


Figure 4.2.2.3—1: Insoluble Residue Results for Inter-Laboratory Study on German Cement.

The insoluble residue contents determined were 16.39% lower for F2 and 27.87% lower for the inter-laboratory comparisons compared to those determined by BAM. The statistical significance of the results is a topic of separate discussion however, it is worth mentioning that the results appear to show discrepancy and would require statistical analysis to quantify the significance of the discrepancy.

Determining the insoluble residue content was also found to be difficult on all the other cements. Further discussion follows.

Table 4.2.2.3—1 shows the results of the insoluble residue contents for the various cements in the study.

Cement	Insoluble Residue First Attempt (%)	Insoluble Residue Second Attempt (%)	Insoluble Residue Third Attempt (%)	Insoluble Residue Fourth Attempt (%)
B	17.62	25.34	17.96	17.52
C	0.55	3.91		
F1	1.24	0.51		
F2	0.51	1.91	1.15	
BAM	0.61			
G	1.01	1.92		

Table 4.2.2.3—1: Insoluble Residue Results for the Different Cements in the Study

The procedure of EN 196-2 (2005) requires that two samples be tested. EN 196-2 (2005) requires that if the difference of insoluble residue content between the two samples being tested differs by more than 0.08% for samples being tested for the first time or 0.1% for routine tests, then the test has to be repeated. Thus, the reason for the different attempts shown in Table 4.2.2.3—1.

The insoluble residue content is approximately 17.52% for Cement B. Cement B is a composite cement containing between six and twenty percent of fly ash and slag. This outcome was expected based on the work of Abeyruwan et al (2012) who found that the fly ash cement in their study had a high insoluble residue content.

From this test, it could be concluded that perhaps SANS 50197 (2000) recognizes that fly ash cements would naturally have high insoluble residue content. Perhaps the code recognizes that it would unimportant to prescribe limits for fly ash containing cements. This could be motivated by considering that the amount of insoluble residue would depend upon how much of fly ash the manufacturer blends.

It is speculated based on literature, such as from Pavía & Walker (2011) and Gikunoo (2004) dealing with the role that fly ash has in cement that the amount of which a manufacturer would blend depends on a wide range of factors ranging from availability of extender, requirements that have to be met in terms of strength, setting time and durability to mention a few. Thus, prescribing a limit for fly ash containing cements would not seem reasonable if the supposition made herein is correct.

The intention of investigating the insoluble residue content of cement G (CEM II A-L 42.5N) was to investigate reason as to why EN 196-2 (2005) does not prescribe any limits for type II cements.

In both attempts to determine the insoluble residue, the allowable difference of 0.08% and 0.1% mentioned above between the samples tested was exceeded. Even though the exact content could not be determined, it would be sufficient to conclude that the limestone cement has a low insoluble residue content which ranges between 1.01 and 1.92% and would pass the test for insoluble residue if EN 196-2 (2005) prescribed a limit even though it does not.

It is unclear as to why EN 196-2 (2005) does not prescribe limits for such type II cements. However, some reasons can be speculated. It appears that for the limestone cement investigated, prescribing a limit on the insoluble residue content is unimportant. CEM II cements in general allow for blending of extenders ranging from slag, fly ash and silica fume to mention a few.

Thus, depending on what material is blended, the insoluble residue content could be high or low. The contents would be high if the blend were to contain extensive amounts of fly ash as fly ash could result in high insoluble residue contents based on the findings of cement B.

Nonetheless, the insoluble residue content for cement G is considered to be low since it is under the five percent which SANS 50197 (2000) prescribes. Furthermore, from the work of Beddey et al (2013), it was expected that the insoluble residue content would not have exceeded the allowable limit prescribed by SANS 50197 (2000).

For a manufacturer, it would be quite clear that having records of the amount of insoluble residue for all their cements would be beneficial, even if it is not a requirement stipulated by SANS 50197 (2000). The insoluble residue content could give a fair indication of the amount of extender present, especially fly ash.

With regards to the German cement, F2, the insoluble residue for the German cement the first time was accepted since the content between the two samples being tested differed by 0.11% which was close to 0.1%. However though, the test was repeated since the code requires that if the test is not a routine test in a sense that the test is not conducted regularly, the difference should only be limited to 0.08%.

The second time the German cement was tested, the contents of the two samples differed by 2.36%.

After the third attempt, the difference was found to be 0.000345% implying that the most accurate result was after this attempt. This observation is noteworthy. Even though the smallest percentage difference was noted in the third attempt, the result is misleading.

The third attempt yielded an insoluble residue of 1.15% whereas the BAM result was 0.61. This would imply that the content is 88.52% above the actual insoluble residue limit. Comparing the results of the first attempt to those of BAM results, the percentage differences were found to be 16.39%. These findings show that the insoluble residue test is a sensitive test and that it is more likely that the errors made in testing the two samples were done carefully and consistently so much so to the point that the differences are found to be insignificant.

The insoluble residue for the Pakistani cement was conducted twice. For cement B, in both attempts, finding the insoluble residue was proved to be futile as the differences were exceedingly high between the duplicate samples. It was decided that further attempts would be abandoned as the content appeared to be under five percent which is the limit prescribed by SANS 50197 (2000).

Table 4.2.2.3—2 shows the insoluble residue contents and compares the results to the limits prescribed by SANS 50197 (2000).

Cement	Insoluble Residue (%)	SANS 50197 (2000) Limit (%)	(%) Difference Relative to SANS 50197 (2000) Limit
B	17.52	No Requirement	250.4
C*	2.23	5	-55.4
F1	0.51	5	-89.8
BAM	0.61	5	-87.8
G*	1.7	No Requirement	-66
*Approximate Content, Based on Average from Different Attempts			

Table 4.2.2.3—2: Comparison of Insoluble Residue Results to SANS 50197 (2000)

SANS 50197 (2000) requires that only CEM I and CEM III cements have a maximum allowable limit of insoluble residue. All other cements do not have to satisfy any limits with regards to insoluble residue content.

Cement B, as has already been discussed contained fly ash. The high insoluble residue content and the large percentage difference of 250.4% compared to the limit of 5% prescribed in SANS 50197 (2000) is testimony to the fact that the cement contained fly ash.

Cement C a Blast furnace slag cement, cement F1, the Pakistani cement as well as the German cement had passed the requirement of insoluble residue content with between 55.4%, 89.8% and 87.8% less insoluble residue content.

Cement G, the limestone cement has 66% less insoluble residue content than the maximum permissible content of 5%. There is no requirement for this cement in terms of insoluble residue. However, the exercise of determining the insoluble residue content nonetheless, perhaps, could indicate that this cement has indeed only limestone and no other extender, especially fly ash. This information could be useful for forensic work where it is important to establish the extenders present in a cement.

From all the attempts to determine the insoluble residue content, it could be gathered that the insoluble residue test was extremely sensitive test and demanded great skill.

The sources of error could be attributed to several reasons. There could have been variations in the preparation of the reagents used in the analysis, the efficiency of the conductor in performing the experiment as well as possible variations in the testing conditions.

4.2.2.4. Implication of Findings

Based on the results obtained, the plain Portland cements and the blast furnace cement are within acceptable limits prescribed by SANS 50197 (2000).

Cements containing fly ash are expected to have high insoluble residue contents. This was the case with the fly ash cement tested by Abeyruwan et al (2012) as well as in the present study with cement B.

The limestone containing cement in this research report had a low insoluble residue content of approximately 1.7%. The findings appear to be reasonable based on the results of Beddey et al (2013) who found that for between zero and thirty five percent of limestone addition to cement, the insoluble residue content altered from 0.66% to 1.56% only.

Some of the implications of high insoluble residue contents may be reduced early strength development as well as poor durability (Arwui, et al., 2011). The plain Portland cements (cements F1 and BAM) and the blast furnace cement (Cement C) have insoluble residue

contents that are within acceptable limits. The implication of the findings would suggest that durability and early strength development would not be a problem due to cement adulteration.

4.2.3. Chloride Content

The measured sulphate contents can be found in Appendix 2.3.

4.2.3.1. Assumptions and Limitations

The chloride contents were determined for five cements. The chloride test was only performed once. It is assumed that the results are representative and accurate of cements manufactured at any period during the year.

The source of chlorides may be derived from the raw materials used to manufacture the cement, any chemical enhancers present in the cement, the gypsum as well as the extenders that may be present. The contribution of the different sources towards the total measured chloride content is unknown.

This study is limited to investing the internal content of chloride for the various cements and not the performance of the cements in concrete where chlorinated environments are of concern.

4.2.3.2. Expectations

It was expected that all the cements would pass the chloride test. There was no reason to doubt the certification of the different cements.

4.2.3.3. Results and Discussion

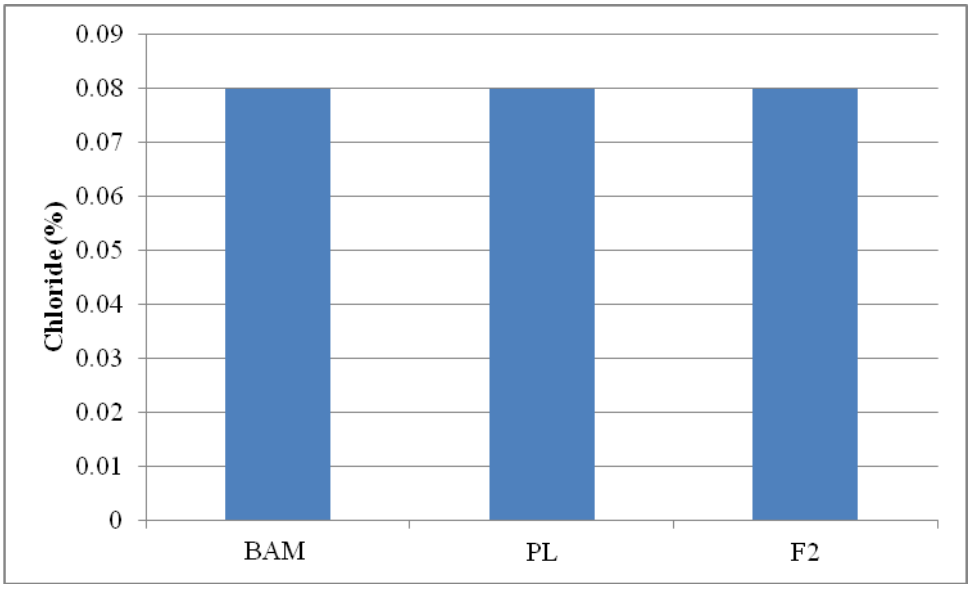


Figure 4.2.3.3—1: Chloride Content Results for Inter-Laboratory Study on German Cement.

From the three tests conducted thus far, namely, sulphate, insoluble residue and chloride content, determining the chloride content was the simplest.

The results of Figure 4.2.3.3—1 (BAM, 2012) shows the least deviation from the Participating Laboratories and BAM. There is a zero percentage differences between the results.

The chloride contents for the various cements in the study are presented in Table 4.2.3.3—1.

Cement	Chloride Content (%)	SANS 50197 (2000) Limit (%)
B	0	0.1
C	0	0.1
F1	0	0.1
F2	0.08	0.1
G	0	0.1

Table 4.2.3.3—1: Chloride Content Results for different Cements in the Study

All the cements satisfied the limits stipulated for maximum allowable chloride content. The German cement had a chloride content of 0.08% which was 80% below the threshold limit of EN 196-2 (2005).

4.2.3.4. Implication of Findings

The chloride contents of the Pakistani, German and the local cements are well with the prescribed SANS 50197 (2000) limit of 0.1%.

4.3. Part 3: Physical Tests

In this section of the report, the cement characteristic strength, setting time, loss on ignition and specific surface area results are presented.

For each test, the assumptions and limitations of the study are first presented. Expected outcomes of the test are then presented. These expectations are then compared to the measured results. Possible sources of error as well as the implications of the findings are highlighted.

Three results are presented for the reference cements from Germany. The results from BAM are ascribed the key word 'BAM.' The results from the Participating Laboratories are ascribed the notation 'PL'. The results of the samples tested for this research report are recognised with the label 'F2'.

The results from the locally tested cements are presented and compared to the outcome of BAM results. In comparing the results of F2 and PL, the BAM results are used as a basis for comparison. It is assumed that the results from BAM give a better representation of the properties of the reference cement.

The reason for opting to use the results from BAM instead is probably because BAM results are more accurate compared to the results of all the participating laboratories. It should be borne in mind that BAM was one of the main coordinators and initiators of the inter-laboratory study. It is reasonable to expect that such an important role would probably have the effect that the institution would take great precaution to ensure that their results are accurate as possible.

4.3.1. Cement Characteristic Strength

The measured cement characteristic strengths can be found in Appendix 3.1.

4.3.1.1. Assumptions and Limitations

With regards to the German cement, the prisms made were tested for flexural and compressive strengths.

SANS 50197 (2000) does not stipulate minimum required flexural strengths for different classes of cements. Instead, SANS 50197 (2000) imposes minimum strength requirements for compressive strength only.

All of the cements besides the German reference cement were only tested for compressive strength and not for flexural strength as there is no requirement in SANS 50197 (2000) for flexural strength.

For each period of testing the German cement, three prisms were made. Each prism was tested for flexural strength. Thereafter, the broken halves of the three prisms which amounted to six specimens (two halves per prism) were tested for compressive strength.

Unlike the German cement compressive strength which was based on an average of six specimens; the local cements compressive strength in the study is based on an average of two specimens and not six.

It is assumed that an average of two specimens is sufficient to infer the compressive strengths of the cements. The testing of the cements except for the German cement was tested at a certified private laboratory (name disclosed for confidentiality reasons). The German cement was tested at the School of Civil and Environmental Engineering at the University of the Witwatersrand using a hydraulic crushing machine capable of testing specimens up to 600kN.

It is believed that the private laboratory tests cements using an average of two specimens due to the large number of routine tests which the private laboratory conducts. It is also believed that the private laboratory has special authorisation from the South African National Association of Standards (SANAS) where routine tests are involved. To receive such authorisation, the private laboratory had to meet requirements of ensuring proper calibration, routine inspections and validations of all their facilities.

With regards to predicting the performance of the different cements, there are many limitations that make the task difficult. Some of the aspects are noted below:

The effects of supplementary cementitious materials such as fly ash and blast furnace slag result in reduced early strength development. However, the presence of activators such as

alkalis as well as increase in the degree of fineness may lead towards improving strength development (Wolhuter, 1972).

The fineness (surface area) of the supplementary cementitious materials used in the cements is unknown. The presence and proportion of strength activators is unknown. Also important to note is that the proportion of extender is also unknown.

A high surface area may enhance early strength development; however, the presence of high proportions of extender content such as fly ash and slag may result in reduced strength (Wolhuter, 1972). The degree to which surface area coupled with extender content is unknown in the study. Furthermore, the quantity of chemical activator present, which could serve to enhance strength where there is a large proportion of extender, is unknown.

Some supplementary materials such as limestone may lead towards enhanced strength development due to filler effects (Neville, 2008). Cements D1 and D2 contained fly ash with limestone. The extent to which the limestone enhances strength or, alternatively, the extent to which fly ash reduces strength is unknown.

An important aspect with regards to the procedure of making the prisms as detailed by SANS 50197 (2000) is the water content. The water to cement ratio is fixed at 0.5. In practice however, the water content could be adjusted in order to satisfy the requirements of workability depending on application. Thus, assessing the cement strengths using a fixed water to cement ratio of 0.5 may not offer a proper assessment of the cements performance in practice in practice.

Fly ash containing cements may lead to improvements in workability (Thomas, 2013). In practice, the amount of water used in a mix could be reduced in order to achieve the same workability in a mix lacking fly ash. The consequence of the reduced water would lead to enhanced strength as the water content has a significant influence on strength development (Fulton, 1964).

Thus, assessing the performance of cements based on a water/cement ratio of 0.5 as stipulated by SANS 50197 (2000) may not be a true indication of the performance of the cements in practical applications where the water content would be adjusted to meet the requirements of the application at hand.

4.3.1.2. Expected Strength Results

It was expected that the class R cements would achieve greater strength compared to the class N cements at two days of testing for compressive strength. The expectation is based on the minimum required strength provided by SANS 50197 (2000). For instance, class 42.5R cements have to achieve at least 18 MPa after two days of testing whereas class 42.5N cements are required to only achieve 8 MPa.

For the three periods of testing, namely, two, seven and twenty eight days, it was also expected that the group of cements belonging to class 32.5 would achieve the least strength. The group of cements belonging to the class 52.5 group was expected to achieve the greatest strength whereas the class 42.5 cements was expected to achieve greater strength compared to the class 32.5 cements but less than the class 52.5 group of cements.

With regards to predicting the performance of the different cements, no speculations are made due to the limited information available. The many limitations that make the task difficult are aptly noted in the previous section of Assumptions and Limitations.

4.3.1.3. Results and Discussion

The flexural and compressive strength results of the inter-laboratory study are presented in Figure 4.3.1.3—1 and Figure 4.3.1.3—2 (BAM, 2012). The observations are first stated and discrepancies noted. Thereafter, the results are discussed. Possible sources of error are stated and the implications of the findings are noted.

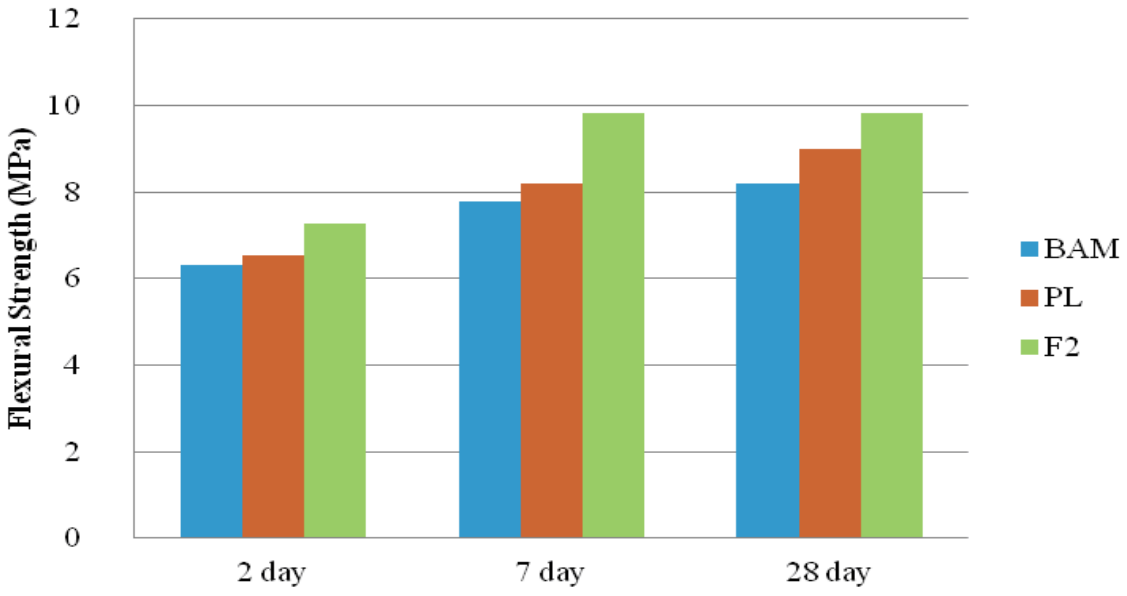


Figure 4.3.1.3—1: Inter laboratory Flexural Strength Results of German Cement

In terms of flexural strength, the results of cement F2 are found to be higher than those from the Participating Laboratories as well as BAM for all three periods of testing. The results of the strengths of samples of cement F2 were greater by 14.9%, 26.6% and 19.5% larger after two, seven and twenty eight days of testing compared to BAM.

The flexural strength results after seven and twenty eight days of testing were found to be 9.8 MPa. The results from BAM showed an increase of 0.4 MPa between seven and twenty eight days of testing (5.1% increase).

The results from the Participating Laboratories show less difference compared to the BAM results. The percentage differences at two, seven and twenty eight days are 3.3%, 5.3% and 9.7%. The strengths for all three periods of testing show that the results obtained by the Participating Laboratories are less than those from BAM.

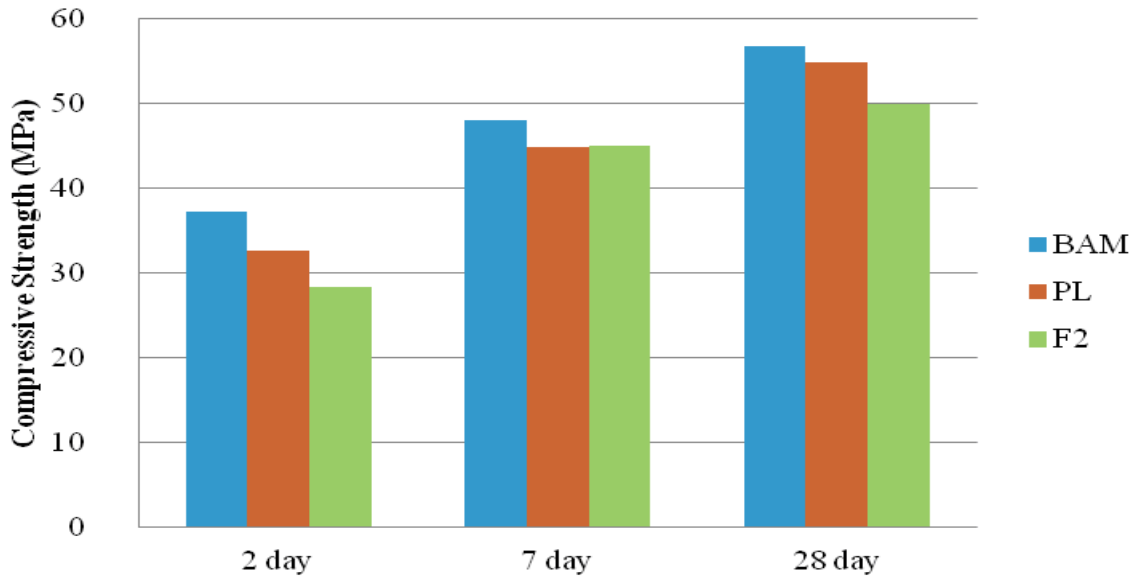


Figure 4.3.1.3—2: Inter laboratory Compressive Strength Results of German Cement

For all three periods, the results of the samples tested at the University of the Witwatersrand (cement F2) are lower than those determined by BAM. The results of cement F2 at two, seven and twenty eight day strengths are 24.1%, 6.0% and 11.8% lower compared to BAM.

The compression strength results are in contrast to the flexural strength results for the specimens tested at the University of the Witwatersrand. The flexural strength results were found to be greater for all three periods of testing compared to the flexural strength results obtained by BAM. On the contrary, the compressive strength results are found to be lower for all three periods of testing.

The compressive strength results from the other Participating Laboratories are also in contrast the flexural strength results upon comparison the BAMs results. The flexural strength results were found to be larger for all three periods of testing whereas the compressive strength results are all lower for all periods of testing.

The compressive strength results of the Participating Laboratories are lower compared to the results of BAM. The percentage differences at two, seven and twenty eight days are 12.3%, 6.5% and 3.3% compared to the results of BAM.

The difference in compressive and flexural strength results could be attributed to differences in load rate, curing conditions as well as calibration of the loading cells of the testing machines.

EN 196-1 (2005) requires that the load rate during testing be maintained at approximately 50N/s.

The hydraulic testing machine at the University of the Witwatersrand was not equipped with a built in feature to control the load rate. The load rate had to be corrected manually by adjusting the amount of hydraulic pressure applied during the testing. This aspect would probably have been the main factor contributing to the differences in the strength results observed.

The load rates adopted by the participating laboratories are unknown. It is not clear whether the load rate may have been a significant factor contributing towards the differences in measured strength results by the various participating laboratories compared to the results of BAM.

Furthermore, the exact conditions of curing are unknown. It is unclear whether variations in the curing may have been prevalent. Nonetheless, the prevalence of variations in curing conditions would be an important factor to consider and would require further investigation.

The results of the characteristic compressive strengths of the various cements of this research report are presented in Figure 4.3.1.3—3through to Figure 4.3.1.3—5 after testing at two, seven and twenty eight days. The results are also compared to the limits stipulated in SANS 50197 (2000).

Figure 4.3.1.3—3shows the compressive strength results obtained after two days of testing.

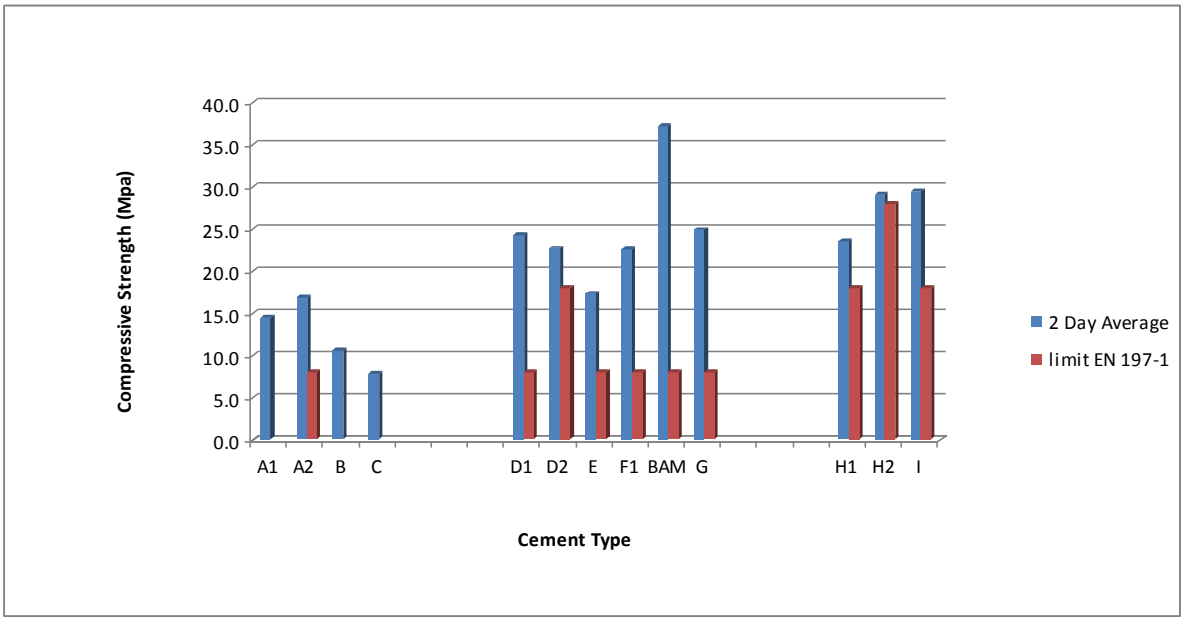


Figure 4.3.1.3—3: Cement Characteristic Strengths after Two days of Curing

SANS 50197 (2000) imposes that if cements are tested once off, the minimum strength requirement at two days of testing class 32.5R and class 42.5N cements must be greater than or equal to eight Mega Pascals. For routine testing, at least 10 MPa must be achieved. This research report makes use of the limits prescribed for once off testing, that is, eight Mega Pascals.

There is only one class 32.5R cement in the study, namely cement A2. The strength recorded is 16.8 MPa. This cement exceeds the minimum required cement strength by 110%.

It was stated in the previous section that the class R cements were expected to achieve greater strength compared to the class N cements. Cement A2, which belongs to class 32.5R satisfies the expectation. This cement achieves greater strength compared to all class 32.5N cements.

There is no minimum strength requirement for the class 32.5N cements. Nonetheless, the percentage differences between the observed strengths and the minimum strength requirement of eight MPa stipulated by SANS 50197 (2000) for class 32.5R cements shows that all the cements would have passed the test for minimum strength at two days if these cements were 32.5R cements, except for cement C. Thus, despite these cements being classified as normal strength gaining class 32.5N cement, these could be considered to perform just as well as rapid gaining strength class 32.5 R cements.

To explain further, the percentage difference of cement A1 indicates that this cement achieved 80% greater strength compared to the prescribed minimum of 8 MPa. Also, cement

B yields 32.5% higher strength compared to the limit of 8 MPa prescribed. Cement C however, only fails to achieve the minimum required strength by 3.8% which could be considered to be negligable.

With regards to the class 42.5 cements, all of the cements satisfy the minimum strength requirements. The minimum strength requirement for class 42.5N cements is stipulated to be 8 MPa and for class 42.5R cements, 18 MPa is stipulated by SANS 50197 (2000).

The German cement, which is indicated by label BAM, achieved 37.3 MPa. This cement achieved the greatest strength compared to all the cements in the study, including the class 52.5 cements. This cement achieved 107.2% higher strength compared to the minimum required strength of 18 MPa.

Cement D2, also a class 42.5R cement exceeded the minimum requirement. This cement achieved 22.7 MPa which is found to be 4.7 MPa more than the minimum required strength of 18 MPa or, in terms of percentage difference, showed 26.1% greater strength.

When discussing the class 32.5 cement strength results, it was mentioned that the class 32.5N cements satisfied the strength requirements of class 32.5R cements and could possibly be classified as class 32.5R cements. Similarly, the class 42.5N cements could be classified as class 42.5R cements. The statement is based on the observation that most of the cements have been found to yield greater strength than the minimum required amount of 18 MPa stipulated by SANS 50197 (2000) for 42.5R cements.

All of the cements achieved more than 18 MPa except cement E. Cement E achieved a strength of 17.3 MPa. This cement belongs to the class 42.5N group. The measured strength is extremely close to 18 MPa. In terms of percentage difference, cement E fails to meet the 18 MPa target by only 3.9%.

Despite cement D2 being a class 42.5R cement, there are three other types of cements which achieved greater strength, namely cements D1, G and BAM.

Cement D2 contains between six and twenty percent of fly ash and limestone, the same as cement D1 except that cement D1 is a class N cement and not a class R cement.

Cement D1 is 6.6% greater in strength compared to cement D2. It is not clear as to why cement D1 exceeded the strength of cement D2; however, possible reasons could include the geological source of the materials, the type and proportion of chemical activators present in the cements as well as the degree of surface area.

Cement G contains limestone ranging between six and twenty percent. One of the effects of limestone is a filler effect (Hewitt, 1998). This could be a possible reason for the 9.7% greater strength recorded compared to cement D2.

The BAM cement is a plain Portland cement. Perhaps the absence of extender could be a reason to attribute the 64.3% greater strength observed. However, items such as the mineralogy and surface area must be accounted conducted to support such speculation.

With regards to the class 52.5 cements, the minimum required strength for class 52.5 N cements is stipulated to be at least 18 MPa whereas for class 52.5R cements, it is required that such cements attain at least 28 MPa (SANS 50197, 2000).

It is noted that cement H2, which achieved 29.1 MPa had met the minimum requirement of 28 MPa by a mere 3.9%. It would be important to note that SANS 50197 (2000) requires that the minimum strength must be 30 MPa if the cement is tested routinely. In this case, if the characteristic strength limits were used, the cement would have failed the test. However, since this is a once off study, cement H2 is considered to perform satisfactorily.

Cement I achieved the greatest strength from the three cements in the class 52.5 group. Cement I contains between six and twenty percent fly ash whereas cements H1 and H2 are plain Portland cements.

It was mentioned earlier that fly ash has the effect of reducing early age strength. However, the result of cement I indicates otherwise. The enhanced strength could be attributed to a high surface area as well as the presence of a chemical activator.

It is noticed from the results presented in Figure 4.3.1.3—4 that some of the cements from the class 32.5 achieve good strength results as some of the cements the class 42.5 class. Also, some of the cements from the class 42.5 group perform just as well as the class 52.5 cements.

To make it clear, cement A2 achieved the greatest strength from all of the class 32.5 cements. Cement E had achieved the least strength from all of the class 42.5 cements. The strength measured at two days for cement A2 is 16.8 MPa and for cement E, 17.3 MPa. Cement E had achieved only 0.5 MPa or 3% greater strength compared to cement A2.

From the class 52.5 cements, the least strength was achieved by cement H1 (23.5 MPa). Three of the class 42.5 cements, namely cements D1 (24.2 MPa) and the German cement (37.3 MPa) and cement G (24.9 MPa) achieved greater strength compared to cement H1 by 3%, 58.7% and 6% respectively.

Figure 4.3.1.3—4 presents the seven day strength results along with the prescribed minimum strength limits prescribed by SANS 50197 (2000).

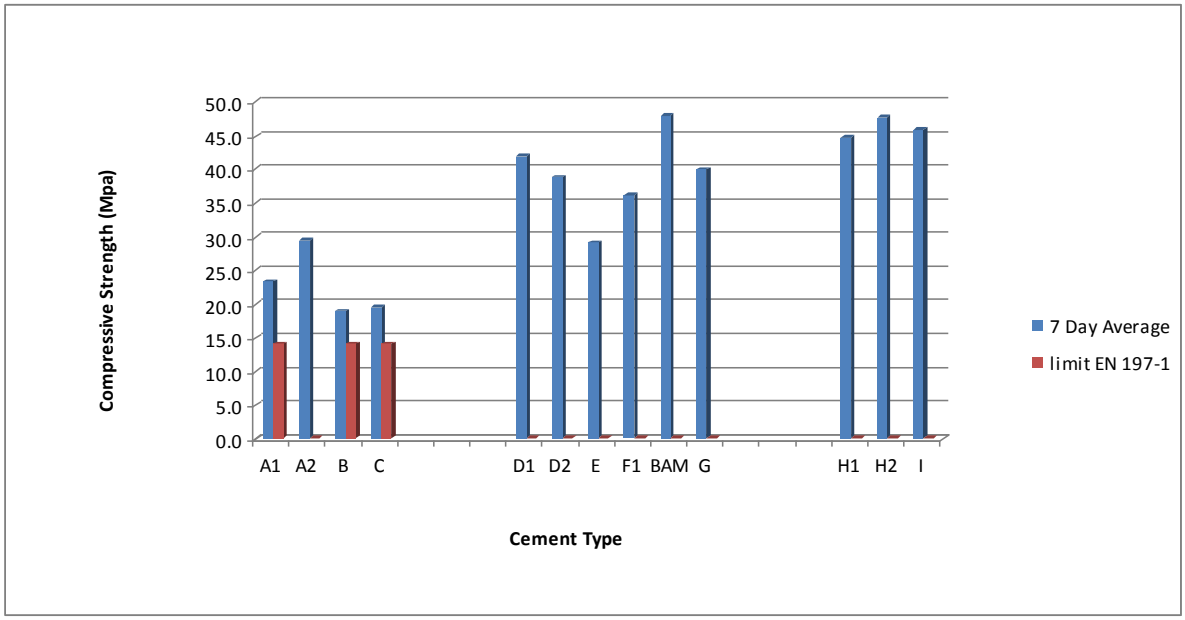


Figure 4.3.1.3—4: Cement Characteristic Strengths after Seven days of Curing

For cements tested at seven days, SANS 50197 (2000) only stipulates limits for class 32.5N cements. All other cement classes have no imposition on the strength achieved. At least 14 MPa must be achieved after seven days of hydration for class 32.5 N cements being tested once off.

Cements A1, B and C belong to the class 32.5 N group. The measured cement strengths exceed the allowable limit of 14 MPa by 45.3%, 17.8% and 21.3% respectively. These percentage differences are not exceedingly high compared to the percentage differences of the two day strength results to the prescribed limit set by SANS 50197 (2000).

Cement A2, the rapid strength gaining cement continued to show greater strength compared to cement A1, the normal strength gaining cement. The strength of cement A2 (29.5 MPa) is 26.6% greater compared to cement A1 (23.3 MPa).

The German cement given by code BAM continues to show greater strength compared to all the other cements, including the class 52.5 cements.

At two days of testing, it was observed that cement E achieved 3% greater strength compared to cement A2. At seven days however, cement A2 achieved 29.5 MPa and is found to have greater strength compared to cement E which achieved 29.1 MPa. The difference is noted to be 0.4 MPa or 1.4% in terms of percentage difference.

The strength of cement H1, the 52.5 cement normal gaining Portland cement proved to show greater strengths at seven days unlike at two days compared to cements D1 and G which were stronger. At seven days, comparing cements D1 (42.0 MPa) and G (40 MPa) to the measured strengths of cement H1 (44.7 MPa), cement H1 is greater in strength by 6 and 10.5%. Cement H1 is, nonetheless, lower in strength compared to the German cement by 6.9%.

The strengths observed after twenty eight days of hydration are presented in Figure 4.3.1.3—5.

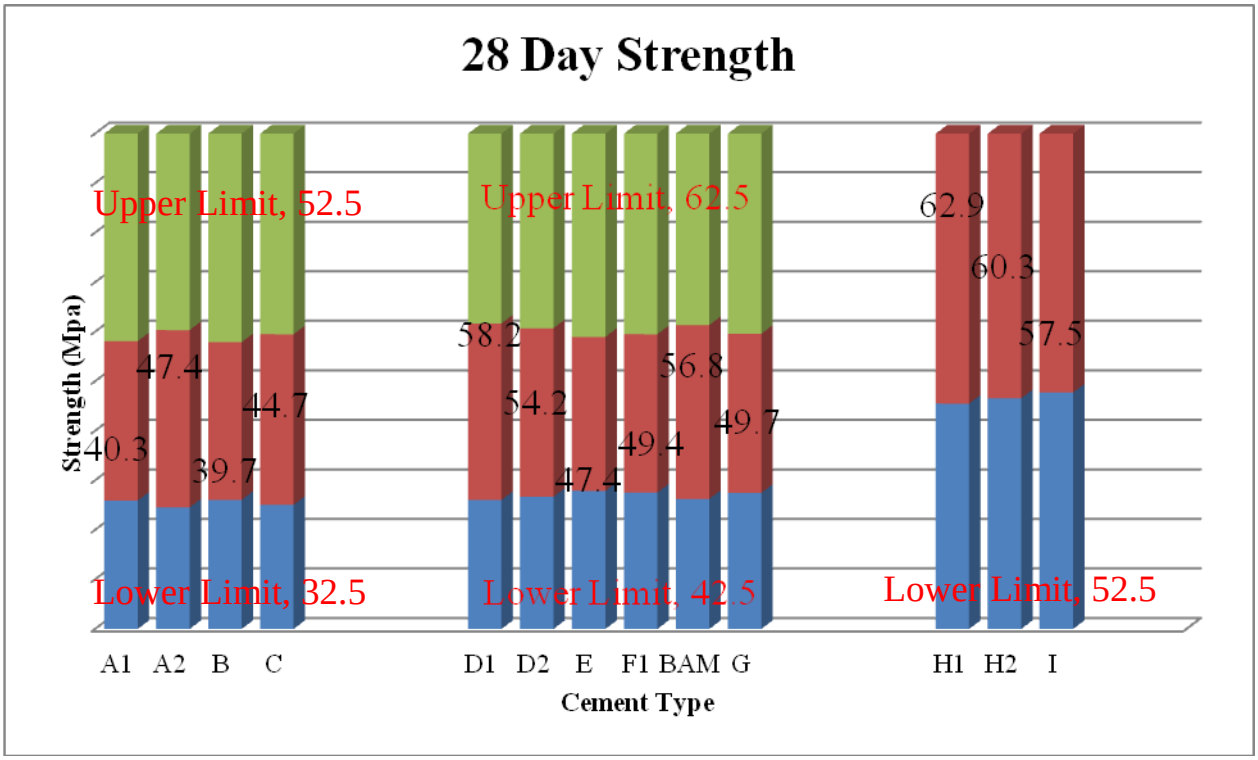


Figure 4.3.1.3—5: Cement Characteristic Strengths after 28 days of Curing.

SANS 50197 (2000) prescribes minimum and maximum strength values for routine tests on cement after twenty eight days of hydration. The range of strengths have to at least range between 32.5 and 42.5 MPa for class 32.5 cements and between 42.5 and 52.5 MPa for class 42.5 cements. Class 52.5 cements only have to achieve at least 52.5 MPa, no maximum requirement is stipulated.

SANS 50197 (2000) also prescribes minimum strength requirements for class 32.5, 42.5 and 52.5 cements for cements tested once off at twenty eight days of testing. However, no prescription is provided for the maximum allowable strengths to which the cement classes must achieve. The prescribed minimum strength limits are 30, 40 and 50 MPa for the three classes of cements respectively.

It was decided to use the prescribed strength limits of routine tests instead of the once off limits prescribed. The reason for opting to utilize the prescribed test limits of routine tests would allow for determining whether any of the cements fall outside of the prescribed strength ranges of minimum and maximum strength. If the single values were used from the once off tests, then it would not be possible to obtain this indication.

From Figure 4.3.1.3—5, it is noted that all the cements satisfy the minimum prescribed limits. It is also noted that none of the cements exceed the allowable maximum prescribed limits.

With regards to strength development of the 32.5 cements, cement A2 yielded the greatest strength (47.4 MPa). Cement C attained a strength of 44.7 MPa. Cement A1 produced a strength of 40.3 MPa followed by cement B which accomplished 39.7 MPa.

At two and seven days, the order in which the cements had gained maximum strengths was different. At two days, the order of strengths listed from greatest to smallest was A2, A1, B then C. At seven Days, the order was A1, A1, C then B.

Cement C had shown relatively low strengths in the early stages; however, the twenty eight day strengths showed that this cement resulted in the second greatest rate of development of strength.

The average strength of cement A1 is 40.3 MPa whereas cement A2 is 47.4 MPa. Cement A2 would thus be considered to be superior to cement A1 in terms of strength by 17.62%. These two cements were similar in composition but differed in terms of the rate of gain of strength. Cement A2 has rapid gaining strength properties whereas cement A1 was a normal strength gaining cement.

Some of the class 32.5 cements could be classified as class 42.5 cements based on the observed strength results.

For instance, cement A2 approaches the upper limit of 52.5 MPa which SANS 50197 (2000) prescribes for class 32.5 cements at twenty eight days of testing by 9.7%. This cement also satisfies the lower limit of 42.5 MPa prescribed for class 42.5 cements. At two days, the cement also satisfied the strength requirement of a class 42.5N cement.

Cements A1 and B were more or less equally in between the upper and lower prescribed limits. Cement A1 was 24.0% greater than the lower bound but 23.2% lower than the upper bound whereas cement B revealed 22.2 and 24.4% for the same bounds.

With regards to the strength development of the 42.5 cements, the cements which achieve the greatest strength in decreasing order are: D1 which is found to have 58.2 MPa. The German cement, given by label BAM, which attains 56.8 MPa. D2 is recorded to have accomplished 54.2 MPa. Cement G succeeds in attaining 49.7 MPa followed closely by F1 which is found to have accomplished 49.4 MPa. Finally, cement E obtains a strength of 47.4 MPa after twenty eight days of hydration.

The chemical notion of cement D1, CEM II/A-M (V-L) 42,5N, an ordinary strength gaining cement, is similar to Cement D2, except for the fact that cement D2 is a rapid strength gaining cement. Cement D1 exceeds the strength of cement D2 by 4 MPa or compared to cement D2, in terms of percentage difference, 7.4%.

The trend of strength development is different at two and seven days. At two days, the order of cements gaining the greatest strengths were: BAM, G, D1, D2 and F1 then E. At seven days, the order was recoded to be: BAM, D1, G, D2, F1 then E.

Cement E of class 42.5 strength achieved the same strength as cement A2 which belongs to the class 32.5 group of cements.

The German cement is no longer stronger than any of the class 52.5 cements as was noted previously at two and seven days.

Cement D1 (58.2 MPa) is found to be marginally stronger compared to cement I (57.5 MPa) by 1.2% and could be considered to be equal statistically.

Cement D1 (58.2 MPa) almost neared the upper bound of 62.5 MPa but fell short by 7.0%. The German cement also fell short by slightly less (9.2%). Cement D2 (54.2 MPa) revealed to be 13.4% less compared to the upper bound. Cements E (47.4 MPa), F (49.4 MPa) and G (49.7 MPa) were closer to the lower bound of 42.5 MPa by 11.4, 16.1 and 16.9%.

The two day and seven days strengths of cement H2 were greater by 23.83% and 6.6%, however, after 28 days, cement H1 shows greater strength. Cement H1 exceeds H2 in terms of strength by just 4.31%.

Cement I, which is of class 52.5 strength but a fly ash cement appeared to have similar strength compared to cement D1 which was of class 42.5 but also a fly ash cement. In fact, cement D1 achieved greater strength compared to cement I.

The composition of cement I is CEM II/A-V 52,5N whereas the composition of cement D1 is CEM II/A-M (V-L) 42,5N. Cement I has between 6-20% fly ash whereas cement D1 has between 6-20% of fly ash and limestone.

The strength of cement D1, 58.2 MPa, compared to cement I, 57.5 MPa is 1.2% greater. The implication of this finding could imply that it would be more affordable to purchase cement D1 as opposed to cement I since both cements give similar strengths.

A possible reason to explain the similar strengths between the two cements could be through considering the effect of the limestone. Limestone could have had a filler effect which could have led to an improvement in strength. This aspect could explain why cement D1 attained greater strength compared to cement I.

The minimum required strength according to SANS 50197 (2000) was stipulated to be 52.5 MPa. Cement I had exceeded the minimum requirement by 9.5%. Cement H2 was 14.8% greater in strength compared to the minimum requirement and cement H1 was found to be 19.7% greater in strength.

4.3.1.4. Implication of the Findings

With regards to the two day strength results, the class N cements could just as well be classified as class R cements.

In order to predict the performance of the different cements, several factors have to be accounted. The factors affecting strength may include the type of extender, the proportion of the extender, the geological source as this affects the composition and in turn the hydration characteristics, the degree of fineness, the type of chemical activator as well as the quantity of activator used.

It could be argued that a number of the cements have been “over designed” in a sense that the mixes exceed minimum strength requirements. To explain further: From a manufacturing perspective, of concern would be the physical and chemical characteristics that make up the cement. The manufacturers could have possibly developed the constituents in such a way that would satisfy the minimum strength requirements and in such a way that the strengths do not exceed the minimum strengths too greatly as well.

At two days of testing, cement D1 was found to exceed the minimum specification of 8 MPa by 202.5%. Cement D2 only exceeded the minimum specification of 18MPa by 26.1%. Considering that cements D1 and D2 are of the same composition, it could be argued that,

cement D1 had been “over designed” since the minimum requirement was only specified to be 8MPa and so, far exceeded the minimum requirement.

After twenty eight days of testing, cement D1, which attained 58.2 MPa, was found to be close to the upper bound of 62.5 MPa by 7%. Cement D2 was also found to be close to the upper bound by 13.4%. Both cements had to only achieve at least 42.5 MPa in order to be classified as 42.5 Cements.

From the above discussion, it would be more suitable to consider twenty eight day strengths when deciding whether cement under investigation had been “over designed” or not.

From the 32.5 cements, cement A2 was greater than the minimum strength requirement of 32.5 MPa by 45.8%. The cement which deviated the least from the minimum strength requirement was that of cement B (22.2%). From the 42.5 cements, the cement which deviated the least from the minimum requirement was cement E (24.2%). From the 52.5 cements, cement I deviated the least from the minimum strength requirement and was found to be 9.5% greater in strength compared to the upper bound of 52.5 MPa. Cement H1 showed the greatest deviation and was found to be 19.7% greater in strength than the minimum prescribed limit.

With regards to the preference of the different cements, certain issues may have to be addressed. Some of the issues may be: (a) How workable are concrete made using the cements? (b) What is the minimum duration for strength to be achieved before the moulds can be stripped? Or (c) what extenders present in the cement would be desirable for certain durability considerations? However, if the criteria for selecting a cement based on early strength, then Table 4.3.1.4-1would provide an indication.

Decreasing Order of Strength →					
Class 32.5 Cements					
A2	A1	B	C		
Class 42.5 Cements					
BAM	G	D1	D2	F1	E
Class 52.5 Cements					
I	H2	H1			

Table 4.3.1.4-2: Order of Strength Development of Cement at Three Days

From the class 32.5 cements, cement A2 would be the most desirable. From the class 42.5 cements, the German cement would be the most preferred from the imported cements and cement G would be the most preferred from the local cements. From the class 52.5 cements, cement I would be most desirable however, the strength of cement H2 was almost the same as I and could be just as preferred.

If the criteria for selecting a cement is based on ultimate strengths which are assumed to be the twenty eight day strengths, then Table 4.3.1.4-2 provides an indication.

Decreasing Order of Strength →					
Class 32.5 Cements					
A2	C	A1	B		
Class 42.5 Cements					
D1	BAM	D2	G	F1	E
Class 52.5 Cements					
H1	H2	I			

Table 4.3.1.4-3: Order of Strength Development of Cement at Twenty Eight Days

From the class 32.5 cements, cement A2 would be the most preferred. From the class 42.5 cements, cement D1 would be the most preferred and from the class 52.5 cements, cement H1 would be the most preferred.

From the class 32.5 cements, cement C would have been the last option for early strength as a criteria but comes in as the second option if the late strength development is desired.

From the class 42.5 cements, it is interesting to note that Cement E is the least favourable for both early and late strength development.

Cement I may have been the most favourable from the class 52.5 cements for early strength development, however, the long term performance based on the twenty eight day strengths shows that this cement would be the least favourable.

It should be stated that the test was a once off test. To conclusively determine whether a cement fails to meet the minimum required strength, it would be necessary to assess the performance of the cement over extended periods. This would ensure statistical reliability.

Furthermore, the statistical variance would indicate how well cement manufacturers perform. Cement that shows drastic variability in terms of strength could be regarded to be undesirable. This aspect could lead to varying quality of concrete works in large projects where purchases are made at different periods. Variations in concrete properties could lead to technical and legal issues which have been omitted in this discussion.

Greater number of tests would also ensure that outliers are sorted out appropriately before firm conclusions can be drawn on the performance of cements.

4.3.2. Setting Time

The results of the setting times for the inter laboratory study are first presented followed by the results of the setting times for the different cements in the study.

The assumptions and limitations are discussed. The results for the water demand as well as the initial and final setting times are presented and the findings are elaborated upon. The section concludes with implication of the findings.

The measured setting time results can be found in Appendix 3.2.

4.3.2.1. Assumptions and Limitations

The measurement of setting times were only conducted once. The temperatures are assumed to have been constant at 20+/-2°C for the duration of the test as required by EN 196-3 (2005). The needles and plunger for the setting time were assumed to conform to the requirements prescribed by EN 196-3 (2005).

EN 196-3 (2005) requires that the ball of the hand be used to gently tamp the mould in order to compact and remove voids in the paste after the cement paste is filled in the mould. It is assumed that the effort used by the operator in tamping the mould was uniformly distributed and consistent.

From the literature review, factors affecting the setting times include the cement particle fineness, the composition of the cement, the presence of gypsum, the formation of mineral compounds such as CSH and ettringite as well as the phases in the cement.

The degrees of fineness for most of the cements are unknown. Furthermore, the exact compositions of the cements, presence of extenders, gypsum, mineral compounds as well as strength enhancers present are unknown. In addition, the quantities of extender, gypsum, mineral compounds and strength enhances that may be present are unknown.

The amount of water used for the determination of the setting time is based on the requirements which as stipulated in EN 196-3 (2005) which dictate that the depth of plunge must range between four and eight millimetres.

Depending on the experience of the operator in determining the depth of plunge, the amount of water could vary. This amount of water has an influence on the setting as water is a requirement for hydration. It is assumed that the experience of the operator in conducting the test was adequate.

The results of the setting times obtained by BAM are used in the results and discussion as it is assumed that the results are much more accurate compared to the results obtained by the participating laboratories as it is reasonable to expect that since BAM was one of the main initiators of the inter-laboratory study, they would've emphasised on accuracy.

4.3.2.2. Expected Results

SANS 50197-1 [Table 3, p 16] stipulates that the initial setting time of 32.5 cements tested once off be greater than one hour. For class 42.5 cements it is necessary that the initial setting time is greater than fifty minutes.

It is expected that all the cements would satisfy the requirement stipulated by SAN 50197-1 for initial setting time summarised above.

The lack of information on the degrees of fineness, compositions of the cements, gypsum, mineral compounds as well as strength enhancers present makes it difficult to predict the setting times for the different cements.

Nonetheless, it is expected that cements containing slag and fly ash may display delayed setting times (Shi, 2004; Hewitt, 1998).

Furthermore, it is expected that the setting times of the class 32.5 cements will be the longest whereas the setting times of the class 52.5 cements will be the quickest. In turn, the setting times of the class 42.5 cements would vary between the class 32.5 and class 52.5 cements.

The basis for the above expectation are based on the cement characteristic strengths obtained in Section 4.3.2 and on the notes provided by Shi who mentioned that hydration products such as the formation of CSH lead to stiffening and in turn setting of the cement paste.

From Section 4.3.2, it was found that the cements with the largest strength are the class 52.5 cements whereas the cements with the lowest strength were the class 32.5 cements. The strengths of the class 42.5 cements varied between those of the class 32.5 and class 52.5 cements.

Thus, the above findings suggest that the class 52.5 cements are more reactive and hydrate fastest whereas the class 32.5 cements are less reactive and hydrate the slowest. In turn, the class 42.5 cements reactivity and hydration rates vary between the class 32.5 and class 52.5 cements.

4.3.2.3. Results and Discussion

Table 4.3.2.3—1 presents the water demand as well as the initial and final setting times of the results from the participating laboratories (BAM, 2012).

	BAM	PL	F2
Water Demand for Standard Consistency (%)	28.6	28.7	29.6
Initial Setting Time (mins)	2hrs25mins	2hrs11mins	2hrs23mins
Final Setting Time (mins)	3hrs01mins	3hrs25mins	3hrs10mins

Table 4.3.2.3-1: Setting Characteristic Results of Inter-Laboratory Study

It is apparent that the water demands between all three tests are similar. Cement F2 is found to require 3.5% more water when compared to BAM results. Cements tested by the Participating Laboratories require almost the same content of water. The percentage difference is found to indicate that those cements tested require 0.35% less water for standard consistency which could be considered to be negligible.

The implications of the findings on water demand show that determining the water demand for standard consistency is not a challenging task and can be determined reasonably accurately.

The initial setting times of cement F2 are lower by only 1.4% (negligible) compared to the cement tested at BAM. The cements tested by the Participating Laboratories differ by 9.7%. These findings suggest that the initial setting times can be reasonably accurately predicted.

The final setting times of the cements after comparing cement F2 and those tested by the Participating Laboratories are found to be greater by 5% and 13.3% after comparing to BAM results. The findings suggest that the results obtained with F2 is more accurate compared to the results obtained by the participating laboratories.

4.3.2.4. Results and Discussion

The results and discussion are separated for the class 32.5, 42.5 and 52.5 cements.

Table 4.3.2.4—1 shows the results obtained for the class 32.5 cements.

Cement [C]	Type of Cement	Water demand %	Initial Set time	Final set time (time after initial set)
32.5 Cements				
A1	CEM I/V B-V 32.5N	32.6	4hrs23mins	2hrs15mins
A2	CEM IV B-V 32.5R	28.6	4hrs36mins	0hrs48mins
B	CEM V/A (S-V) 32.5 N	30	4hrs21mins	0hrs59mins
C	CEM III A 32.5 N	30	4hrs07mins	0hrs44mins

Table 4.3.2.4-1: Setting Characteristics of 32.5 Cements

SANS 50197-1 [Table 3, p 16] stipulates that the initial setting time of 32.5 cements tested once off be greater than one hour. It is noticed that the initial setting times for all the cements satisfied the requirement. There is no stipulation for the final setting time.

The water demands of all the cements are similar. Cement A1 has a 14% greater water demand compared to cement A2. Cement B and C are found to have the same water demand.

It was speculated that class R cements would set faster compared to class N cements. From the results of cement A1 and cement A2, it is noticed that the initial setting times are similar. Cement A2 sets 13 minutes after cement A1.

However, the final setting times indicate cement A2 sets quicker compared to cement A2. Cement A2 set one hour and twenty seven minutes before cement A1. This finding suggests that cement A2 is indeed a class R cement and cement A1 is indeed a class N cement.

From the 32.5 cements, namely cements A, B and C, the cement with the longest initial and final setting times were cements A2 and A1. The cement with the shortest initial and final setting times was cement C.

Cements A1 and A2 are fly ash cements whereas cement C is a GGBS cement. Cement B is a composite cement containing slag and fly ash. The setting times of cement B ranged between those of the slag and fly ash cement. The initial setting time of cement B occurred fourteen minutes after that of cement C and fifteen minutes before that of cement A2.

Cements A1, B and C are all normal gaining strength cements whilst cement A2 is a rapid gaining strength cement. The final setting times of cement A1 compared to cement B and C are different whereas the final setting times of cements B and C were comparable to that of cement A2.

The final setting time of cement A1 occurs 1hr16mins and 1hr31mins minutes after when compared to cement B and C or, in terms of percentage difference, 128.8 and 206.8%. The final setting times of cements B and C compared to cement A2 differs by eleven and sixteen minutes or, in terms of percentage difference, 22.9 and 34%.

This finding suggests that class R cements do not necessarily set quicker compared to class N cements as was speculated.

From the findings, it could be inferred that fly ash affects setting time to a greater extent than mixes containing slag or mixes of fly ash blended with slag as was the case with cements A2, C and B.

The setting characteristics of the class 42.5 cements are presented in Table 4.3.2.4—2.

Cement [C]	Type of Cement	Water demand %	Initial Set time	Final set time(time after initial set)
D1	CEM II A-M (V-L) 42.5N	29	3hrs57mins	0hrs41mins
D2	CEM II A/M (V-L) 42.5R	28.9	4hrs05mins	1hrs03mins
E	CEM II B-M (S-V) 42.5N	29.8	3hrs34mins	0hrs50mins
F1	CEM I 42.5 N	26	2hrs36mins	0hrs30mins
BAM	CEM I 42.5 N	28.6	2hrs25mins	0hrs36mins
G	CEM II A-L 42.5N	29.6	2hrs10mins	0hrs49mins

Table 4.3.2.4-2: Setting Characteristics of 42.5 Cements

Cement F1 requires less water compared with cement BAM. Both cements were plain Portland cements. However, cement F1 only required 26% water for standard consistency. Comparatively, cement BAM required 10% more water. Besides cement F1 which required 26% water for standard consistence, all the other cements require similar water contents ranging between 28.6% and 29.8%.

SANS 50197-1 [Table 3, p 16] requires that the initial setting times of 42.5 cements being tested once off be greater than fifty minutes. It is noticed in Table 4.3.2.4—2 that the initial setting times for all the cements satisfy the requirement stipulated. SANS 50197-1 does not prescribe any requirements for the final setting times.

The initial setting times of cement D2 is lower compared to cement D1 by eight minutes or 3.37% indicating that both cements were similar in terms of initial setting time. The final setting time of cement D2 is lower by twenty two minutes or 53.7%.The initial setting times of cement F1 is eleven minutes higher compared to cement BAM or, in terms of percentage, exceeds cement BAM by 7.6%. The final setting time on the other hand shows that cement BAM sets higher by fifteen minutes or 50%.The cement with the shortest initial setting time is cement G (2hrs10mins) whereas the cement with the longest setting time is cement D2 (4hrs05mins). The difference in setting times between these two cements is 1hr55mins or

88% relative to cement G.The cements with the shortest and longest final setting times are cements F1 and D2. Cement E2 set thirty three minutes earlier than cement D2. In other words, cement E2 differs by 110%.

Cements F1and BAM are the imported cements. F1 is the Pakistani cement whereas BAM is the German cement. These cements are plain Portland cements. The initial setting times of these cements are shorter upon comparing the setting times to the local cements excepting cement G. It is expected that the setting times would be longer for cements F1 and BAM than the other class 42.5 blended fly ash and slag cements as such extenders have the effect of prolonging setting time (Thomas, 2013).

Cement D2 belongs to the class R group whereas cement D1 belongs to the class N group. It was mentioned in the previous section that class R cements are expected to set quicker compared to class N cements. However, cement D1 shows faster signs of setting instead of cement D2.

It is thought that the water contents could have explained the difference in setting time. The water contents, however, are similar. Cement D2 consumed 0.3% less water for standard consistence compared to D1. The initial setting times only differ by eight minutes whereas the final setting times differed by twenty two minutes.

There could be several reasons to explain the difference in setting times between cements D1 and D2 as well as the other cements for that matter as mentioned earlier in the assumptions and limitations section. For instance, it could be possible that cement D2 contains greater quantities of Gypsum which could explain the delayed setting compared to cement D1. However, the composition

The setting characteristics of the class 52.5 cements are presented in Table 4.3.2.4—3.

Cement [C]	Type of Cement	Water demand %	Initial Set time	(time after initial set)
H1	CEMI 52.5N	31.6	3hrs43mins	00hrs42mins
H2	CEM I 52.5R	31	3hrs34mins	0hrs46mins
I	CEM II A-V 52.5 N	30.6	4hrs32mins	0hrs52mins

Table 4.3.2.4-3: Setting Characteristics of 52.5 Cements

All the class 52.5 cements require similar water contents for standard consistency. The normal gaining strength Portland cement, namely cement H1 requires 1.9% more water than the rapid gaining strength Portland cement, that is, cement H2. Compared to cement H1, the fly ash containing cement of I requires 3.2% less water. These differences could be assumed to be negligible statistically.

Class 52.5 cements are required to at least set after forty minutes according to SANS 50197-1 [Table 3, p 16] for cements being tested once off. It is noticed in Table 4.3.2.4—3 that the initial setting times for all the cements satisfy the requirement stipulated. No prescription is given for the final setting times.

The initial and final setting times of cements H1 and H2 are similar and differ by nine and four minutes respectively. Cements H1 and H2 are Portland cements. H1 is a normal strength gaining cement and shows longer initial setting times compared to H2, the class R cement. The times differed by only 4.2% and can be assumed to be negligible statistically.

The fly ash containing class 52.5 cement, namely cement I is found to have longer initial and final setting times compared to the plain Portland cements. This finding is expected as fly ash has the effect of delaying setting time (Thomas, 2013).

4.3.2.5. Implication of Findings

The initial setting times of the local and imported cements vary approximately between two and a half hours to four and a half hours. The final setting times for most of the cements occur after approximately 45 minutes. The water demands for standard consistence between all the cements are also similar and vary approximately between 26 and 32.6%.

The differences in water required for standard consistence could be attributed to the differences in chemical composition, extender content, fineness and handling of the operator.

Extenders such as fly ash would result in an improvement in workability which could lead to reduced water demand for desired consistency. However, most of the cements had similar water demands for standard consistence. Thus, it could be inferred that water demands for all classes of cements were similar.

The differences in observed setting times could be attributed mainly to the chemical composition of the cements. For instance, the quantity of Gypsum. Greater quantities of Gypsum would have the effect of prolonging setting time.

The effect of composition explains the quick setting characteristics of certain cements. For instance, cement G which is a limestone containing cement.

The Pakistani and German cements show the shortest setting times. High temperatures make handling, compacting and finishing concrete on site difficult. This is explained by Ahmadi (2000). Hot weather climatic conditions may result in a high demand of water and at the same time accelerates slump loss together with setting times.

It could be argued that it might be more beneficial to use a cement having a long setting time in hot weather to counter the effects of accelerated setting. In this case, the Pakistani and German cements would be unsuitable compared to the local cements (excepting cement G which set very fast) which have fairly extensive setting times compared to these imported cements.

4.3.3. Loss on Ignition (LOI)

The results of the German test are presented along with the results obtained from testing the various cements in the study.

The measured loss on ignition results can be found in Appendix 3.3.

4.3.3.1. Assumptions and Limitations

EN 196-2 (2005) stipulates that in order to determine the loss on ignition value of a cement, the cement must be ignited between 925 ℃ and 975 ℃.

In order to determine the loss on ignition value, the cement is ignited for a certain amount of time until it reaches constant mass. This period could be as early as five minutes as is suggested by EN 196-2 (2005). For the present study, the cements were allowed to remain for more than 12 hours in the furnace, thereby guaranteeing complete ignition. It is assumed that this approach would not introduce unwanted chemical or physical reactions that could lead to variances in the loss on ignition between tested in this study and those tested in strict accordance with EN 196-2 (2005).

4.3.3.2. Expected Results

SANS 50197 (2000) stipulates a loss on ignition limit of 5% for CEM I and CEM III cements only. Cement F1 and cement F2 belongs to the class I group. Cement C belongs to the class III group. It was expected that these three cements would satisfy the requirement of loss on ignition since there was no indication on the cement bags to indicate otherwise.

4.3.3.3. Results and Discussion

Figure 4.3.3.3—1 (BAM, 2012) shows the results obtained by the various participating laboratories in determining the loss on ignition content.

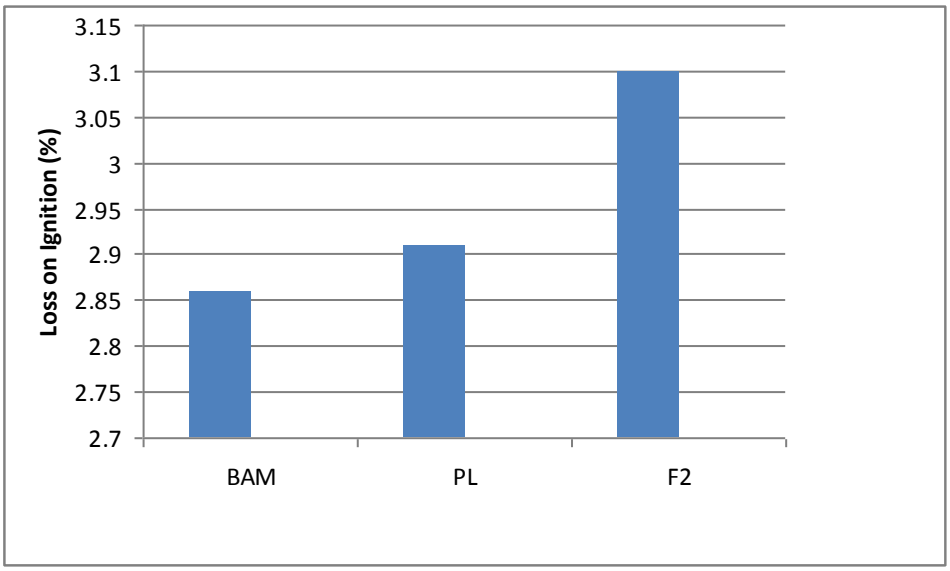


Figure 4.3.3.3—1: Loss on Ignition Results for Inter-Laboratory Study

The loss on ignition values is all similar. The percentage difference relative to the results obtained by BAM is 8.4% for cement F2 and 1.7% for the participating laboratories.

The results of the loss on ignition for the various cements are tabulated in Table 4.3.3.3—2.

Cement	Loss on Ignition (%)	EN 196-2 (2005) Limit (%)	Percentage Difference Relative to SANS 50197 (2000) (%)
B	0.8	No limit	84
C	-0.3	5	106
F1	1.7	5	66
F2	3.1	5	38
G	9.2	No limit	-84

Table 4.3.3.3-2: Loss on Ignition Results for different Cements in the Study

It is interesting to note that the Cement C resulted in a weight gain rather than a reduction of weight compared to the other cements.

In the literature review concerning loss on ignition (refer to Section 2.3.2) it was discussed that certain cements could reveal a weight gain upon ignition. Such observations occur if there are sufficient quantities of certain iron minerals.

It is not clear what iron minerals might have been present in cement C. Examples of iron bearing phases in the cement could have been $C_4Al_2fe_2O_{10}$ and feMgO as was noted in the study of Duda (1989) who had found weight gain of oxide contents after conducting ignition

tests. Perhaps the cement contained magnetite which oxidized into hematite, resulting in a weight gain as was the case in the study of Costa et al (2010).

The above speculation would have to be confirmed by conducting an analysis into the iron bearing phases of cement C.

The Pakistani cement showed less loss on ignition value compared to the German cement relative to the limit stipulated in the code. Perhaps the difference could be attributed to less carbon in the Pakistani cement as well as the better storage conditions of the Pakistani cement.

To explain what would be meant by better storage conditions, it could be that between the time when the cement was manufactured, the German cement may have been exposed to the atmosphere and drawn moisture resulting in pre-hydration to some extent. However, this speculation would be subject to debate since the typical LOI values of the German and Pakistani cements of routine tests from the manufacturers was not available.

There is no requirement of loss on ignition issued in SANS 50197 (2000) for composite cements. This could possibly be explained through considering that one of the purposes of a loss on ignition test would be to infer the amount of carbon. Since composite cements would allow for limestone to be incorporated into the cement, it would be clear than that such a cement would have a high loss on ignition value since limestone is a carbonaceous material ($CaCO_3$). Cement G was a limestone containing cement.

The low loss on ignition content of cement B would indicate that this composite cement had little or no limestone blended and indeed only contained slag and fly ash as the manufacturer had noted in the description: CEM V/A (S-V) 32.5N, where S represented slag and V fly ash.

4.3.3.4. Implication of Findings

The ordinary loss on ignition for the plain Portland cement is found to be within the prescribed limits stipulated by SANS 50197 (2000).

The loss on ignition test can be used to infer the amount of carbon present in a material as was noticed for cement G.

The loss on ignition can also be used to infer the degree of pre-hydration as was noticed with the higher loss on ignition values associated with cement F2 compared to the result from BAM.

4.3.4. Specific Surface Area

4.3.4.1. Assumptions and Limitations

The Results and Discussion section on the inter-laboratory study will show that the results obtained from testing cement F2 using the Blaine Apparatus at WITS compared to the cement tested at BAM shows a significant difference.

There were other local cements tested using the same Blaine Apparatus at WITS. It is assumed that on the basis that the same Blaine Apparatus was used; the errors associated with the measured specific surface areas were constant.

4.3.4.2. Expected Results

It was expected that the class 32.5 cements would have specific surface areas less than the class 42.5 cement.

However, it was expected that the specific surface area of the Pakistani cement which is a class 42.5 cement would have the least specific surface area since this cement yielded the most workable mix. Refer to section 4.4.1 on page 4-51 for the workability results.

4.3.4.3. Results and Discussion

Laboratory	BAM	PL	F2
Blaine Specific Surface (cm^2/kg)	4260	3574	3250

Table 4.3.4.3-1: Specific Surface Area Results of Inter-Laboratory Study

The results obtained by the different participating institutions (BAM, 2012) showed a significant discrepancy. Cement F2 was found to be 23.7% lower compared to BAM whereas the Participating Laboratories on the whole had 16.1% lower values.

Cement Type	Specific Surface (cm^2/kg)	(%) Difference Relative to F2
B	3360	-3.4
C	3310	-1.8
E	3420	-5.2
F1	2880	11.4
F2	3250	0.0
BAM	4260	-31.1
G	3630	-11.7

Table 4.3.4.3-2: Specific Surface Area Results of Various Cements in Study

The cement which had the greatest specific surface area was the German cement according to the results obtained by BAM. However, it should be mentioned that the German cement tested for specific surface area at the University of the Witwatersrand had a lower degree of fineness. The fineness of cement F2 (3250 cm^2/kg) was measured to be 31.1% lower compared to the same German cement tested at BAM (4260 cm^2/kg).

Assuming that the BAM results are most accurate for similar reasons given in Section 4.2, the results indicate that the calibration of the equipment at the University of the Witwatersrand may have not been corrected properly. Thus, it was decided to compare all the cements tested at the University of the Witwatersrand to cement F2 instead of the cement tested at BAM since the relative errors would be obviated to allow for comparison of the performance of the cement specific surface areas.

The cement which had the greatest degree of fineness measured by specific surface area was cement G (3630 cm^2/kg). The fineness was measured to be 11.7% greater compared to the German cement tested at the University of the Witwatersrand.

The Pakistani cement, cement F1 (2880 cm^2/kg) was found to also have a much lower specific surface area compared to the other local cements. This cement was 11.4% less fine than the German cement F2.

Cements B, C and E had marginally less specific surface areas compared to cement F2. The observes percentage differences compared to cement F2 were 3.4, 1.8 and 5.2%

It was noted that the German cement, F2 and the Pakistani cement, F1 had relatively different degrees of specific surface areas despite the similar chemical composition of the cements.

The specific surface area of cements B and C were comparable to the specific surface areas of cements E, F2 and G. Cements B and C were of class 32.5 whereas cements E, F2 and G were of class 42.5. These findings are in agreement with what was expected.

4.3.4.4. Implication of the Findings

The cements with high surface areas are expected to achieve higher earlier strength compared to the cements with low surface areas. However, the composition of the cement must also be taken into account before such a statement can be qualified.

4.4. Part 4: Hydration Studies

This section of the report is separated into four parts. Part one involves studies on the concrete making properties of the cements in terms of workability. Part two presents the

results on the compressive strength of the concrete items investigated. Part three discusses the durability performance of the various cements. Part four reports on the results of the effect of specimen thickness in relation to hydration whereby tile specimens were studied.

4.4.1. Workability

The factors affecting workability, the assumptions, limitations and sources of error are detailed. The indication of the expected slump results for the different cements are mentioned. The results of the slump test are then presented and the observation stated. Thereafter, the significance of the observations is discussed.

4.4.1.1. Assumptions and Limitations

For the same mix, of concrete, discrepancies in slump could be observed by different operators conducting slump tests. This idea is drawn from CCAA (2007) who mention that the tolerance level for a slump test varies between 15 and 20 mm depending on the slump of mixes ranging between zero and one hundred millimeters.

There are several factors that influence the slump test. The factors can range from variable compaction effort, variances in the materials scooped from mixer to fill the mould, temperature variances as well as operator efficiency as was highlighted in the literature review (section 2.4.3). The range of factors show that the variability associated with the test can be extensive.

For the ensuing discussion, it is assumed that slump differences exceeding 20mm between cements imply significant differences in terms of workability. The assumption is drawn from CCAA (2007) whereby it was noted that as much as 20 mm in slump can be tolerated.

There are several limitations to this portion of the study. The quantity of extender present in the cements is unknown. The surface areas of the cements are also unknown. The presence or absence of gypsum which is responsible for the setting of the cements is unknown. The efficiency of the operator in conducting the slump test is assumed to be satisfactory. The effect of variances in humidity and temperature on the different days when the slump tests were conducted is assumed to be insignificant.

4.4.1.2. Expected Slumps

The presence of extender would have an influence on the slump value. Alexander, Ballim and Beaushaushen (2012) mention that slag may improve workability since slag does not have a high affinity for water initially and through better cement dispersion. With regards to fly ash,

improvements in workability may also result due to the spherical particle shape associated with fly ash (Hewitt, 1998).

The exact quantities of extender content are unknown. However, it is speculated that the class 32.5 cements have the largest proportion of extender whereas the class 52.5 cements have the least. In turn, the class 42.5 cements have an extender content varying in between the class 32.5 and class 52.5 groups.

The above speculation is motivated from the results of the prisms tested in Section 4.3.1.3 from the prism two day results, the class 32.5 cement yielded the least strength whereas the class 52.5 cements yielded the greatest strength. The strengths of the class 42.5 cements ranged in between these two classes.

Thus, based on the above, it is expected that the class 32.5 cements would yield the greatest slumps. It is also expected that the class 52.5 cements would achieve the lowest slumps whereas the slumps of the class 42.5 cements would vary between those of the class 32.5 and class 52.5 cements.

4.4.1.3. Observations on Slump Results

Figure 4.4.1.3—1 shows the slump results for concrete made using the different cements.

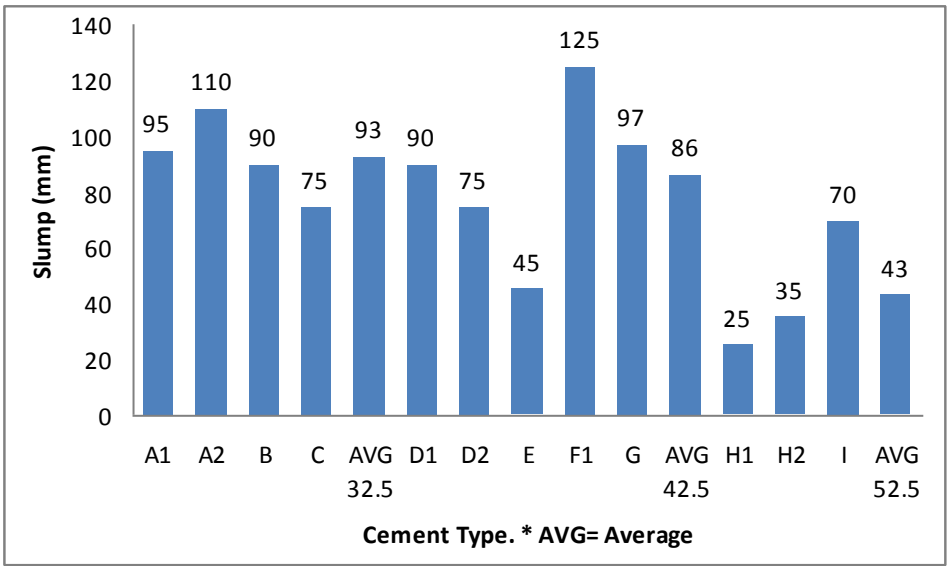


Figure 4.4.1.3—1: Slump Results for Concrete Made Using the Different Cements

In general, from Figure 4.4.1.3—1 the average slump values for the three classes of cements show that the class 32.5 cements yield the greatest workability. The workability measured in terms of slump is 93 mm. Class 52.5 cements show the least workability with an average of

43 mm observed. The workability of the class 42.5 cements is double that of the class 52.5 cements with an average of 86 mm observed.

The above observations confirm the expectations outlined in the preceding section.

Figure 4.4.1.3—2 is presented to discuss the significance of the average slump values between the three classes of cements.

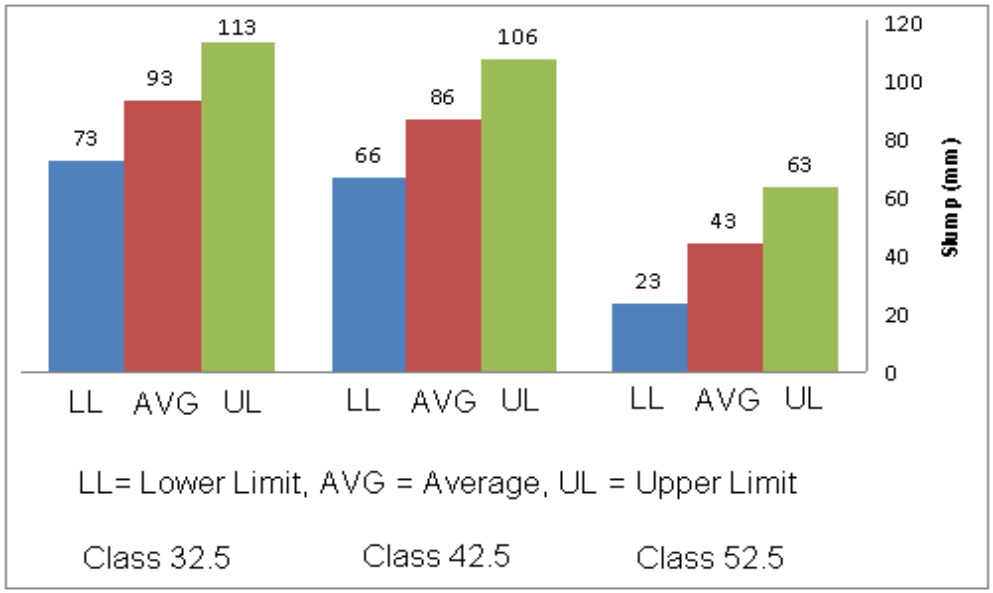


Figure 4.4.1.3—2: Sensitivity of Slump Values

The average slump values for the concrete made using the three cements are 93 mm for class 32.5, 86 mm for class 42.5 and 43 mm for class 52.5 cements. However, the slump test is a variable test. For this reason, upper and lower threshold values are adopted. The values are based on the CCAA (2007) assumed tolerance of 20 mm as a measure of the significance of the workability. The upper and lower limits shown in Figure 4.4.1.3—2 are simply 20 mm more or less compared to the average value of slump recorded.

The differences in average slump between the class 32.5 and class 42.5 cements used to make concrete are considered to be insignificant as the differences recorded is 7 mm which well within the assumed threshold of 20 mm drawn from CCAA (2007).

However, the conclusion would change if the slump was measured to be one of the lower or upper limits instead of the average slump values recorded. To explain this point, suppose that the slump values were 113 mm for concretes made from class 32.5 cements and 66 mm for the class 42.5 cements. The difference in slump would then be 47 mm. This difference would exceed the threshold by 135%. Thus, the difference would be significant to suggest that the workability of the class 32.5 and class 42.5 cements are very different in making concrete.

Similarly, the differences in average slump between concretes made using the class 52.5 cements compared to the concretes made using class 42.5 cements is 43 mm and 54 mm compared to the concretes of class 32.5 cements. These differences exceed the assumed 20 mm threshold by 115% and 170%. The differences suggest that the class 52.5 cements have inferior workability compared to the class 42.5 and class 32.5 cements in making concrete.

However, it has already been discussed that the slump test is a variable test. There could be as much as a 20 mm discrepancy. Suppose the upper limit of 63 mm for the class 52.5 cement is used in the comparison. Furthermore, suppose that the lower limits of the class 32.5 and class 42.5 cements are a better measure of the workability rather than the average and upper limit. In this case, the class 52.5 cement in making concrete differs by only 10 mm compared to the class 32.5 cements and by 3mm compared to the class 42.5 cements in making concrete. The results imply that the workability of the class 52.5 cements are just as good compared to the other two cement classes since the difference between the slump values are under the 20 mm threshold.

From the discussion, it must be appreciated that the slump test is a variable test. Based on the average slump values and the limitations of the test in this study, it can be appreciated that on the whole, the class 32.5 cements have similar workability compared to the class 42.5 cements and in turn, both these classes of cements have better workability compared to the class 52.5 cements in making concrete.

It is now appropriate to discuss the workability of the individual cements in making concrete in greater detail. Figure 4.4.1.3—1 is relevant for the ensuing discussion.

Cements A1 (95 mm) and A2 (110 mm) appear to have similar concrete slump values. A 15 mm difference is noted. The difference is considered to be insignificant as the difference is less than 20 mm. Both these cements yielded the greatest slump values from the four class 32.5 cements which suggest that the best workability can be achieved by using cement A2. Both these cements had fly ash in quantity ranging between twenty one and thirty five percent.

Cement B is of the composite cement type and contains approximately six to twenty percent of slag and fly ash. The content of the blast furnace slag, cement C is anywhere between thirty six and sixty five percent of blast furnace slag. Cement B yields a slump value of 90 mm which is 15 mm greater compared to cement C which has a slump of 75 mm in making concrete. The difference is considered to be insignificant as well.

From the four class 32.5 cements, the slag cement, namely cement C has the lowest slump. Compared to cement A1 and A2, the differences in slump are 20 mm and 35 mm. The differences are considered to be significant and indicate that cement C, the slag cement, yields inferior workability characteristics in making concrete compared to the two fly ash cements. However, it should be borne in mind that the slump values can vary approximately 20 mm implying that the slump of cement C for instance could be between 55 and 95 mm. Thus, if the upper limit of 95 mm is a better representation of the workability, the differences of the slump of concretes made from cement C would compare to cement A1 and A2 would not be significant.

With regards to the class 42.5 cements in making concrete, the slump values range between 45 and 125 mm. to begin with, cement D1 has a slump of 90 mm whereas cement D2 has a slump of 75 mm. The difference in slump value between cements D1 and D2 is 15mm and is regarded to be insignificant. Both cements contain between six to twenty percent of fly ash and limestone. Cement F1, the Pakistani (CEM I 42.5N) cement yielded the greatest slump value from the class 42.5 cements and was measured to be 125 mm. The slump value is also greater compared to all the other classes of cements in making concrete. It is surprising to note that this cement yielded greater slump values even compared to the fly ash containing cements.

One of the main reasons that can possibly explain the high measured slump value of the Pakistani cement (F1) in concrete can be the degree of fineness or surface area. The specific surface area of this cement is documented in Section 4.3.4 of this report.

From the specific area analysis of the six cements tested, cement F1 has the least specific surface area. The low specific surface area analysis shows that cement F1 is rather coarse or in other words, is not very fine. If this supposition is correct, the coarse nature of the Pakistani cement would explain the considerable workability that the Pakistani cement offers in making concrete. To appreciate the significance of the workability of the Pakistani cement, the average workability of the class 42.5 cements excluding the Pakistani cement is 76 mm. The difference between the average slump and the slump of the Pakistani cement is 49 mm.

The basis for hypothesising that coarse cements such as the Pakistani cement results in good workability is inferred from the effect of silica fume on the workability of concrete. One of the main effects of silica fume is that of reduced workability due to the high specific surface area and filler effect (Boddy, Hooton, & Thomas, 2003).

It must be appreciated that the fineness is not the only factor that affects workability. The specific surface area of cement G (a limestone containing cement with limestone ranging between six and twenty percent) was found to have the greatest specific surface area from the six cements tested for specific surface area in Section 4.3.4. Despite the large specific surface area, the slump for cement G is 97 mm. The average slump values of the class 42.5 cements excluding cement G is 84 mm. Using this value, it can be appreciated that cement G yields a greater workability on average compared to the other class 42.5 cements.

Cement E has the lowest slump value for the class 42.5 cements. Cement E contains between 21 and 35% of extenders in the form of fly ash and slag. From the results of the class 32.5 cements, it is found that the fly ash containing cements gave the highest workability. Also, the slag containing cement gave the lowest workability. Perhaps, these findings can be used to explain the low workability associated with cement E.Cements D1 and D2 contain fly ash and limestone whereas cement G contains limestone only. All three of these cements show good workability characteristics. The good workability characteristics of cement F1 is associated with the low specific surface area.

Cement E on the other hand contains fly ash and slag. Furthermore, this cement also has the second greatest specific area from the analysis of section 4.3.4. The presence of slag could contribute towards reducing the workability as was the case with the class 32.5 slag cement (cement C). The high specific surface area could also be a reason that contributes to the low workability of cement E. There can also be other non-technical reasons to explain the low workability such as low operator efficiency in conducting the slump test.

With regards to the workability of the class 52.5 cements, the ordinary Portland cements namely cements H1 and H2, show similar slump values. The slumps were measured to be 35 and 43 mm. The fly ash contained in cement I ranges between six and twenty percent and could explain the significant improvement in workability compared to the Portland cements. Cement I has a slump of 70 mm and is 64.3% more workable compared to cement H1 and 85.7% more workable compared to cement H2.

There is practical benefit in manipulating the workability of a concrete mix. There is further benefit in making use of cements which have an inherently high workability. To explain the significance of using cements that give high workability, consider cement I:

If the water content of cement I has to be adjusted such that the slump values will become similar to the ordinary Portland cements (cements H1 and H2), it would thus imply that

greater strength could be achieved for cement I due to the lower water to cement ratio. The same could be argued for all the other cements which had yielded high workability.

4.4.1.4. Implication of the Findings

The water content of the mixes of the cements which yielded the greatest workability could be adjusted in situations whereby low slumps are desirable. This would result in increased strength.

The fly ash containing cements, namely cements A1, A2, B, D1, D2, E and I appeared to yield superior workability (excepting cement E) compared to all the other cements.

The plain Portland cements, namely H1, H2 which belonged to the class 52.5 group yielded the most inferior workability. However the Pakistani cement belonging to the class 42.5 group of cements yielded the most highest workability. This finding suggest that cement composition is not the only variable that affects workability but other factors such as fineness for instance may also be important to consider.

It is recommended that further tests be conducted in order to improve the interpretation of the workability results presented in this study. The tests can include determining the quantity of extender present, the specific surface areas as well as correlating the slump tests to other tests which measure workability such as the vebe test and compacting factor test.

4.4.2. Compressive Strength of Concrete Specimens

The observations between the three curing regimes are outlined in this section for the different cements investigated. The section is introduced by stating the assumptions and limitations first. Thereafter, brief notes are provided on the expected results. Following the speculations on expected results, the results of the compressive strength tests on the specimens cured in the three different curing regimes are presented and the observations stated. The significance of the results, possible sources of error as well as the implications of the findings is discussed.

The measured concrete strength results can be found in Appendix 4.1.

4.4.2.1. Assumptions and Limitations

The specimens cured in water, air and in the solar chamber were cured under uncontrolled conditions, that is, the temperature and humidity levels were not regulated for the entire duration of the experiment.

The duration of testing for compressive strength was limited to testing at four, eight and twenty nine days.

It is assumed that the humidity levels in the solar chamber were at least 90% for the entire duration of the test and that the average temperature in the solar chamber was approximately six degrees greater than the ambient temperature based on the findings of Uzoegbo (1997).

4.4.2.2. Expected Results

It is expected that the water curing regime would yield the greatest strength. It is also expected that specimens cured in air would show the poorest strength compared to the water and solar curing regimes. In turn, it is expected that the specimens cured in the solar chamber would yield strength greater than specimens cured in air but less than those cured in water.

The basis for the above speculation is based on the following:

Humidity is an important precursor for good strength and durability development (Razak & Sajedi, 2011). Based on this fact, it would be possible to infer that curing in air would result in the poorest strength compared to curing in the solar chamber and in water since the humidity level in the solar chamber is assumed to be at least 90% based on the work of Uzoegbo (1997) and the humidity level in water would be 100%.

However, it is important to also consider the effects of temperature in order to infer the effects of the different curing regimes. The notes provided below are used to impart guidance:

The effects of high temperatures in the early stages of concrete may result in enhanced strength compared with lower curing temperatures though in the long term, strength development could be reduced (Aguado et al., 2009).The reduced ability of water to react with un-hydrated grains of cement due to the already hydrated cement which forms a barrier may explain the reduced overall strength in the long term when high temperatures are employed (Lin & Meyer, 2009).

Razak and Sajedi (2011) better explain the reduction of rate of strength development in the long term through explaining that when temperatures are high, increased hydration rates may be promoted but the hydration products that form do not align themselves in an orderly and adequate fashion. As time proceeds, this poor allignment and placement of hydration products works against allowing further hydration products to form.

It was assumed that the temperature levels inside the solar chamber were at least f six degrees greater than ambient temperatures based on the work of Uzoegbo (1997). The concern with curing under such a regime could be the fluctuations in temperature throughout the day and night. During the day, the temperatures would be higher than ambient and would consequently promote hydration. However, during the night the reduced temperatures could slow down hydration and in turn strength development. For this reason, it is assumed that curing in water would yield higher strength compared to curing in the solar chamber since the temperatures experienced with the water curing regime would be much steadier.

From the above presumptions, it could be argued that the steadier temperatures experienced indoors for the specimens cured in air should yield greater specimen strength than the specimens cured in the solar chamber. However, the importance of humidity explained above cannot be undervalued. The specimens cured in the solar chamber experience greater humidity levels due to the steam that develops during the day when the sun heats the chamber and the water contained.

4.4.2.3. Concrete Strength Observations for the Class 32.5 Cements

Figure 4.4.2.3—1shows the compressive strength results of the class 32.5 cements

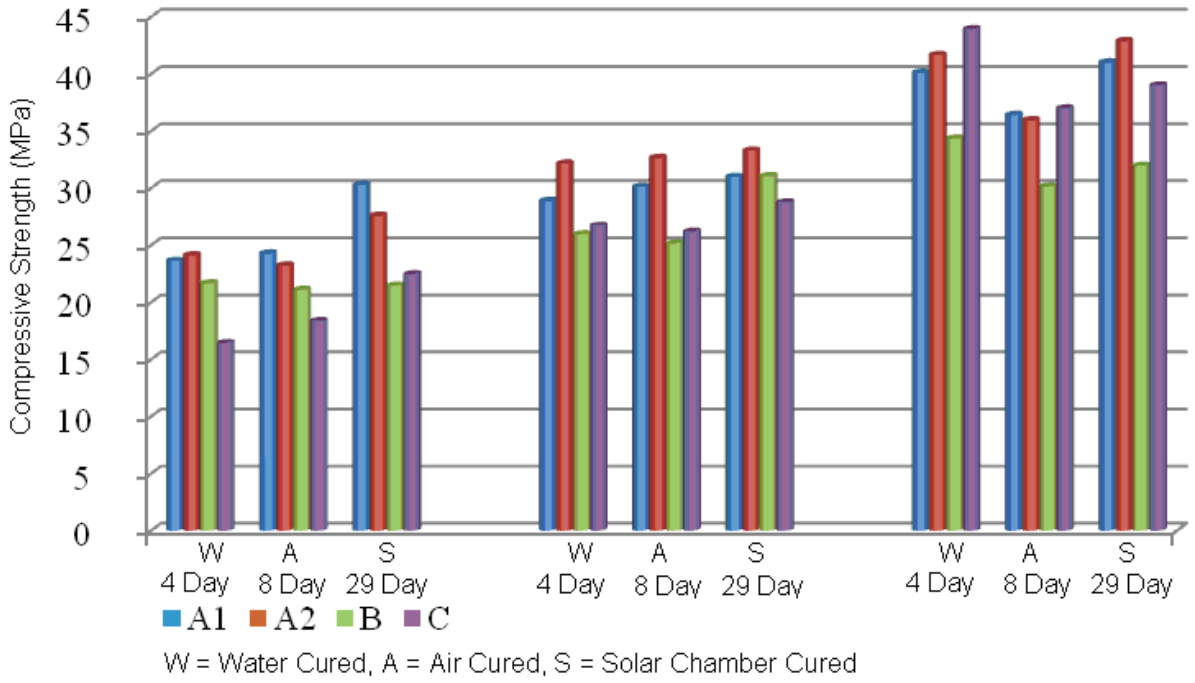


Figure 4.4.2.3—1: Concrete Compressive Strengths of the Class 32.5 Cements

In general, at four days of testing, it is apparent that solar chamber curing resulted in greater strengths compared to curing in water and air.

For cement C, curing in the solar chamber is 36.7% more beneficial compared to curing in water. The next cement that showed the greatest benefit is cement A1 (28.2%). Cement A2 acquired 14.4% greater strength compared to curing in water. Solar chamber cured specimens of Cement B are merely lower in strength by 0.9% which suggests curing in the solar chamber to still be beneficial as the strengths almost equal the strengths of specimens cured in water.

The strengths of samples cured in air are similar to samples cured in water. Specimens of cements A1 and C cured in air exceeded the strengths of specimens cured in water whereas specimens of cements A2 and B are found to be lower in strength than samples cured in water. The percentage differences of the specimens cured in air compared to water are 2.8% for cement A1, 3.7% for A2 and 2.6% for cement B which indicate that curing in air and water yield similar results. For cement C, the percentage difference is 11.8% but in terms of strength, curing in air is found to be 1.9 MPa which could be deemed as insignificant. A possible reason for the similar strengths could be that the himidity of the air was high enough to ensure moist curing however; no measurements of air humidity were taken to ascertain this speculation.

The solar chamber has a positive effect in terms of the strengths attained at eight days of testing. The strength of specimens of cement B that were cured in the solar chamber compared to cements cured in water are 19.6% greater. However, the strength differences are only 4.1 MPa different on average.

Solar chamber specimens of cements A1 and C show similar percentage differences compared to specimens cured in water with relative percentage differences of 7.3% and 7.7% differences. Cement A2 shows the least difference with 3.5% recorded.

It could be appreciated that compared to the four day results, the strengths of cements cured in the solar chamber show less difference to specimens cured in water.

In terms of the strengths attained for specimens cured in air, the strengths were comparable to those cured in water with percentage differences of 4.3% recorded for A1, 1.6% noted for cement A2, 3.1% noticed for cement B and 1.9% observed for cement C.

At twenty nine days of testing, specimens cured in the solar chamber, namely cements A1 and A2 show 2.2% and 3% greater strength compared to specimens cured in water. The differences in strength are merely 0.9 and 1.2 MPa. Cements B and C show 6.9% and 11.2% lower strengths but 2.4 MPa and 4.9 MPa differences in strength respectively.

After comparing specimens cured in air to those cured in water, the percentage differences suggests that moist curing is desirable for greater strength attainment over extended periods. The percentage differences for the respective cements cured in air compared to curing in water is greatest for cement C (15.8%). Cement A2 shows a 13.7% difference followed by cement B which shows a 12.2% difference. Cement A1 shows the least difference with 9.2% recorded.

4.4.2.4. Concrete Strength Observations for the Class 42.5 Cements

Figure 4.4.2.4—1 shows the compressive strength results of the class 42.5 cements.

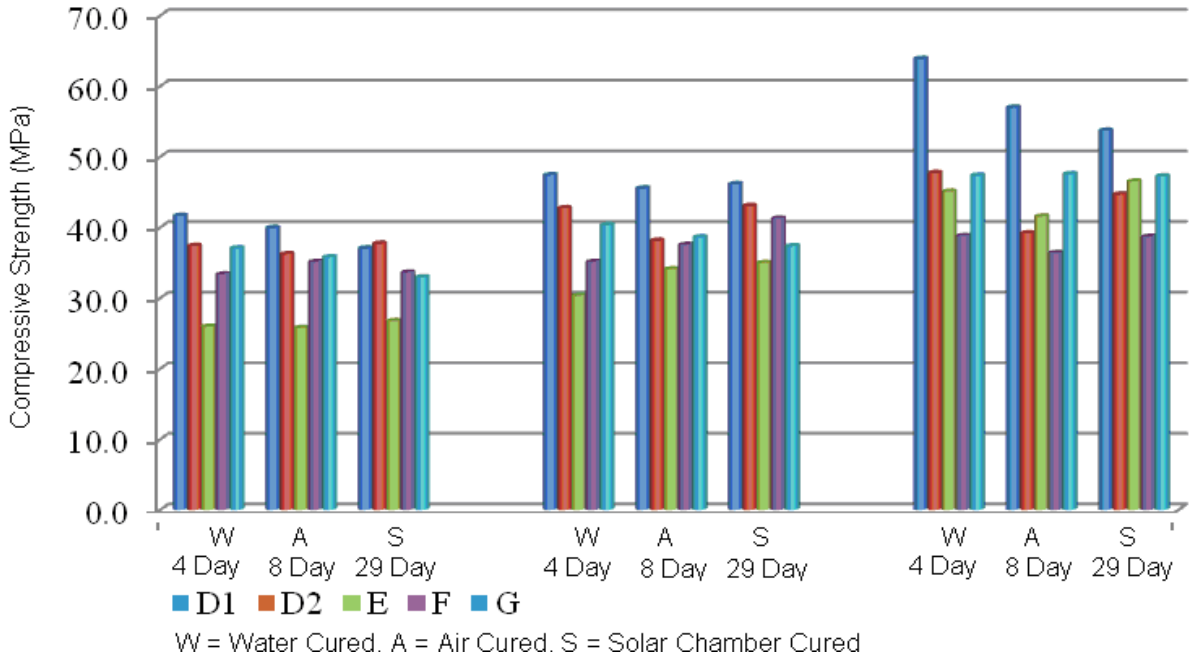


Figure 4.4.2.4—1: Concrete Compressive Strengths of the Class 42.5 Cements

On the whole, the class 42.5 cements appear to show similar strengths for curing in water, air and in the solar chamber after four days. The differences in strength between samples cured in the solar chamber compared to water is 11% for cement D1, 0.9% for D2, 3.1% for E, 0.8% for F1 and 11.1% for G. The differences in strength for samples cured in air compared to samples cured in water are 4.1% for cement D1, 3.1% for D2, 0.6% for E, 5.3% for F1 and 3.4% for G.

With regards to the strength results at eight days of testing, the differences in strength between samples cured in the solar chamber compared to water are found to be lower by 2.7% for cement D1 and 7.4% for cement G. On the contrary, cements D2, E and F1 are greater by 0.7%, 15.4% and 17.5%. The differences in strength for samples cured in air compared to samples cured in water are found to be lower for cements D1, D2 and G by

3.9%, 10.7% and 4.3%. In contrast, cements E and F1 show greater strengths by 10.7% and 12.4%. On the whole, the 42.5 cements appear to show similar strengths for curing in water and air and similar strengths for curing conducted in the solar chamber and in air. These findings appear to suggest that curing regime is inconsequential, however, there could be several sources of error which are outlined in section 4.4.2.6.

With regards to the twenty nine day strength results, besides cements D1 and G, the strengths obtained for all the cements cured in air are less than the cements cured in water and the solar chamber. The percentage differences between specimens cured in air and water for cement G at four and eight days were found to be 3.4 and 4.3%. At twenty nine days however, the strength difference was found to be 0.4% greater for specimens cured in air. It was expected that the specimens would reveal lower strength values considering that the prior two dates of testing, namely four and eight days revealed lower strengths. The difference could be assumed to be insignificant considering that the percentage differences are small.

The percentage difference between specimens cured in the solar chamber compared to specimens cured in water was lower for cements D1, D2, F1 and G by 15.9, 6.4, 0.3 and 0.2% whereas cement E revealed greater strength by 3.2%. With regards to curing in air, the results compared to curing in water revealed percentage differences of 10.8, 17.9, 7.8 and 6.2% for cements D1, D2, E and F1 which were all lower upon comparison.

4.4.2.5. Concrete Strength Observations for the Class 52.5 Cements

Figure 4.4.2.5—1 shows the compressive strength results of the class 52.5 cements

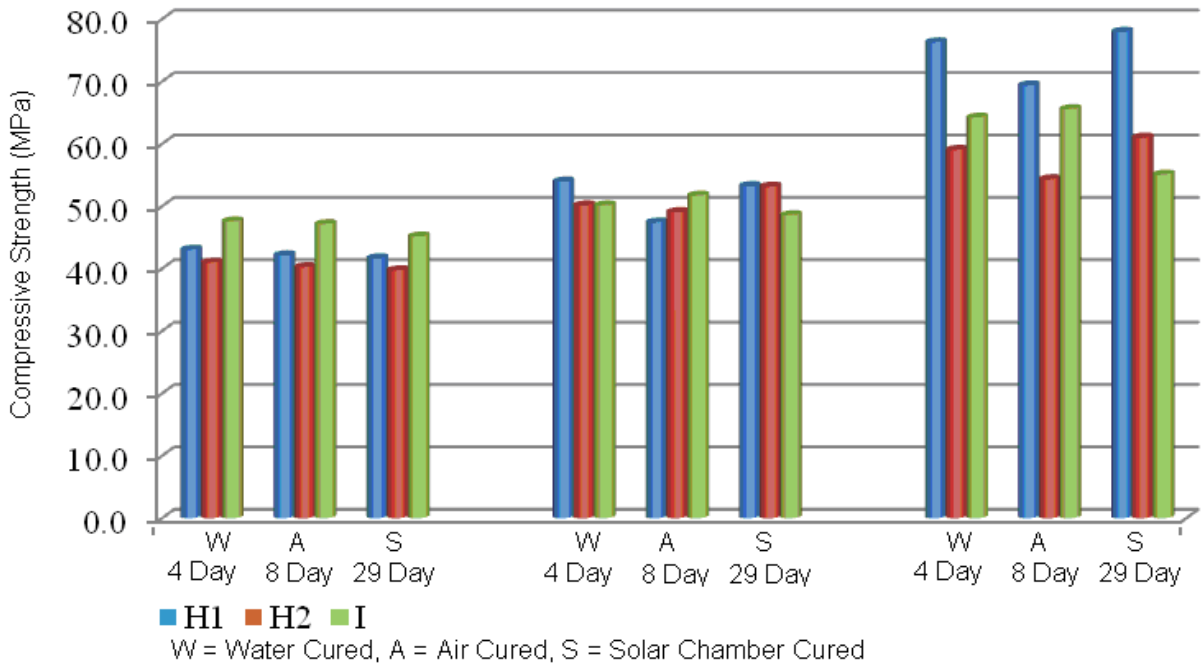


Figure 4.4.2.5—1: Concrete Compressive Strengths of the Class 52.5 Cements

At four days, all the concretes show a similar pattern. All the cements appear to show similar strength as well. Curing in water appears to be marginally superior to curing in air whereas curing in air appears to be marginally superior to curing in the solar chamber. It is not clear why this pattern was observed however, it is speculated that the humidity in the air must have been high. No humidity measurements were taken unfortunately.

The percentage differences of the specimen strengths through curing in air and in the solar chamber relative to water are 0.9 and 5.1% for cement I. For cement H1, the differences are 2.1 and 5.1% whereas for cement H2, the differences are 1.8 and 3.0%.

The strengths of cements H1 and H2 of specimens cured in water are 43.1 and 41 MPa respectively and only differ by 2.1 MPa. Similarly, the strengths of specimens cured in air and in the solar chamber between the two cements differ by 1.9 MPa.

At eight days of testing, in general, it appears that the strength results show a certain degree of scatter. The concrete strengths at four days followed a definite pattern. Curing specimens in water, air and in the solar chamber showed a trend of decreasing strength even though the differences in strengths were minor.

Concretes of I shows greater strength after being cured in air at eight days. Specimens of H1 shows greater difference in strengths between samples cured in water and air compared to

cement H2. Cement H2 shows greater strength for specimens cured in the solar chamber compared to curing in water and air.

However, the differences in strengths between the different curing regimes are minor and could be considered to be insignificant. The strength of specimens cured in air of cement I is 51.7MPa. For the same cement, specimens cured in water area 50.2 MPa which are lower by 1.5MPa or 2.9% compared to air curing. The strength of specimens cured in the solar chamber are found to be 48.6 MPa which differs by 3.1 MPa compared to curing in air and 1.6 MPa compared to curing in water. The strength of specimens cured in water of concretes of H1 are 6.6 MPa greater compared to specimens cured in air or 13.9%. The strength of concretes of H2 cured in water differs by 1.1 MPa which is only 2.2% different. The solar chamber curing regime is found to be 3 MPa different compared to curing in water or 6% in terms of percentage difference for concretes of H2.

The twenty-nine day strengths of concretes of I show a similar trend to the strengths obtained at four and eight days of testing. At four days, curing in air was found to be 0.9% lower than curing in water. At eight days, samples cured in air were found to be 2.9% greater in strength compared to samples cured in water. At twenty-nine days, the strengths are 2.2% greater. The results indicate that concretes of cement I is not adversely affected by curing in water or air. This result appears to be strange and could be a consequence of different sources of error outlined in section 4.4.2.6.

The strengths of concretes of H1 and H2 after being cured in water and in the solar chamber reveal that the curing regime has a marginally beneficial effect. Cement H1 revealed a 1.7 MPa difference or 2.2%. Cement H2 revealed a 1.9 MPa or 3.2% difference.

The differences in strength of specimens cured in air compared to water were greater than curing in the solar chamber. For cement H1, the differences was 6.9% whereas for cement H2, 8%. The results indicate that solar chamber curing has a beneficial effect in the long term compared to curing in air for plain Portland cements.

4.4.2.6. Implications of the Findings

In general, contradicting results were observed in certain cases. However, on the whole from a general point of view, for the four and eight days of testing, it is apparent that the strengths from curing in the solar chamber show marginally greater strength compared to specimens cured in air. After twenty nine days of curing, the strength of specimens from the solar chamber exceeds those cured in air but is similar to specimens cured in water.

The sources of error could be attributed to minor variations in the loading rates when samples were being tested, the average amount of time applied to compact the concrete specimens, possible unevenness in the planes of the cube surfaces.

Perhaps, the major factor to account for the differences noted in strengths at different periods could be attributed to the differences in recorded temperature and humidity levels at the different days of casting.

This would be the most plausible reason since the nearly four hundred cubes were made and tested over a period of two months.

The curing conditions in air and water were uncontrolled.

It is also difficult to draw firm conclusions due to the uncontrolled hydration conditions but the results suggest the importance of continuous moisture in curing as water cured samples, in general, showed good strength development.

4.4.3. Durability of the Cements

In this section of the report, the durability was characterised by sorptivity tests.

The assumptions and limitations of the study are first pointed out. Speculations are then made on the expected sorptivity outcomes.

The results are then presented graphically and a discussion is issued.

The implications of the findings are then highlighted along with possible sources of error.

Appendix 4.2 contains the sorptivity results of the different specimens tested.

4.4.3.1. Assumptions and Limitations

The sorptivity test was conducted after allowing for twenty nine days of hydration in three curing regimes, namely, curing in water, air and in the solar chamber.

Extended periods of testing were not considered.

In this study, the disks were oven dried at a temperature of one hundred to one hundred and twenty degrees Celsius approximately.

This was due to faulty thermostat regulation which was not detected at the time.

It is assumed that the effect of the increased temperature will not significantly influence the results since all the disks experienced this temperature.
However, in reality, this could have serious effects.

High temperatures can lead to deterioration. At approximately 105 degrees Celsius, CSH can deteriorate. At approximately 420 degrees Celsius, calcium hydroxide can experience deterioration (Ye & Zhang, 2013). Thus, it must be stated that the findings in this report will be questionable.

As with the compressive strength tests, the temperatures for specimens cured in air, the solar chamber and in water were under uncontrolled conditions. It is assumed that since the specimens were prepared on the same day for all the three curing regimes, the effects that may have resulted from variable temperature and humidity would have affected all the specimens in the same way and can be disregarded.

Certain discs had fractured during sample preparation. Sorptivity results were not adjusted to account for whether the values appeared to be high or low as it was assumed that the results were accurate and representative due to the small number of samples being tested.

4.4.3.2. Expected Results

In order to speculate the effects of the three different curing regimes, the results obtained from the previous section involving compressive strength testing are used:

From the previous section involving compressive strength testing, even though several discrepancies and contradicting results were observed, it was found that in general, after twenty eight days of testing, specimens cured in water yielded the best strength. The specimens cured in air yielded lowest strength. Finally, the specimens cured in the solar chamber achieved strength ranging in between these two modes of curing regime.

Compressive strength could be useful as an indicator of durability (Ahmad, 2009). Thus, from the findings on compressive strength it can be inferred that the specimens cured in water would yield most superior durability followed by the specimens cured in the solar chamber and lastly the specimens cured in air.

4.4.3.3. Observations for the Class 32.5 Cements

Figure 4.4.3.3—1 shows the sorptivity results of the class 32.5 cements.

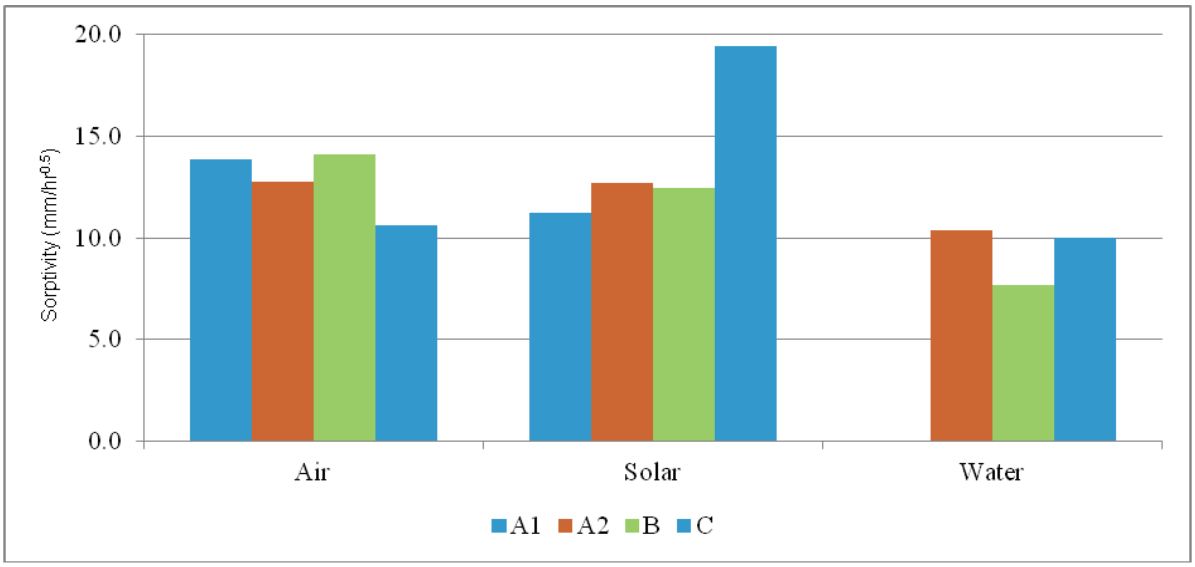


Figure 4.4.3.3—1: Sorptivity of the Class 32.5 Cements

In general, it is noticed that curing in water yielded greater durability compared to curing in air and in the solar chamber. The effect of curing in air and in the solar chamber appeared to show similar results but the solar chamber curing regime does show marginally superior durability.

Specimens of mix A1 and A2 have sorptivity values of 13.9 and 12.8 after being cured in air indicating that cement A2 yields greater durability. However, the sorptivity values of cement A1, recorded to be 11.2 are marginally lower by 11.8% compared to cement A2 which is recorded to have a sorptivity value of 12.7 after being cured in the solar chamber.

The specimens of A1 had to be discarded due to damage that resulted during the coring operation. It would be reasonable to suppose that the sorptivity of A1 would have been similar to A2 as the results for air and solar chamber curing are similar.

The sorptivity results of specimens cured in air and the solar chamber for cement A1 is recorded to be 13.9 and 11.2. The results of the solar chamber specimens compared to air had indicated a marginal difference of 2.7 mm/hr$^{0.5}$ but in terms of percentage different, 20.8% is recorded.

Cement A2 yields 12.8 mm/hr$^{0.5}$ for specimens cured in air and 12.7 mm/hr$^{0.5}$ for specimens cured in the solar chamber indicating a minor difference of 0.1 mm/hr$^{0.5}$ or 0.8% for the solar chamber specimens compared to specimens cured in air. This is contrary to the compressive strength findings.

The sorptivity of specimens of cement A2 cured in the solar chamber are 2.3 mm/hr$^{0.5}$ greater compared to specimens cured in water suggesting that curing in water resulted in 22.1% superior durability.

The sorptivity results of cement B are recorded to be 14.1 for specimens cured in air, 12.5 for specimens cured in the solar chamber and 7.7 for specimens cured in water. The results suggest that water results in 83.1% superior durability compared to curing in air and 62.3% compared to curing in the solar chamber.

Cement C is the only cement that showed less durable concrete for cements cured in the solar chamber where 19.5 mm/hr$^{0.5}$ are recoded whereas, compared to specimens cured in air, only 10.6 mm/hr$^{0.5}$ are noted. However, the sorptivity results for specimens cured in water are similar to those cured in air.

4.4.3.4. Observations for the Class 42.5 Cements

The sorptivity results of the class 42.5 cements follow.

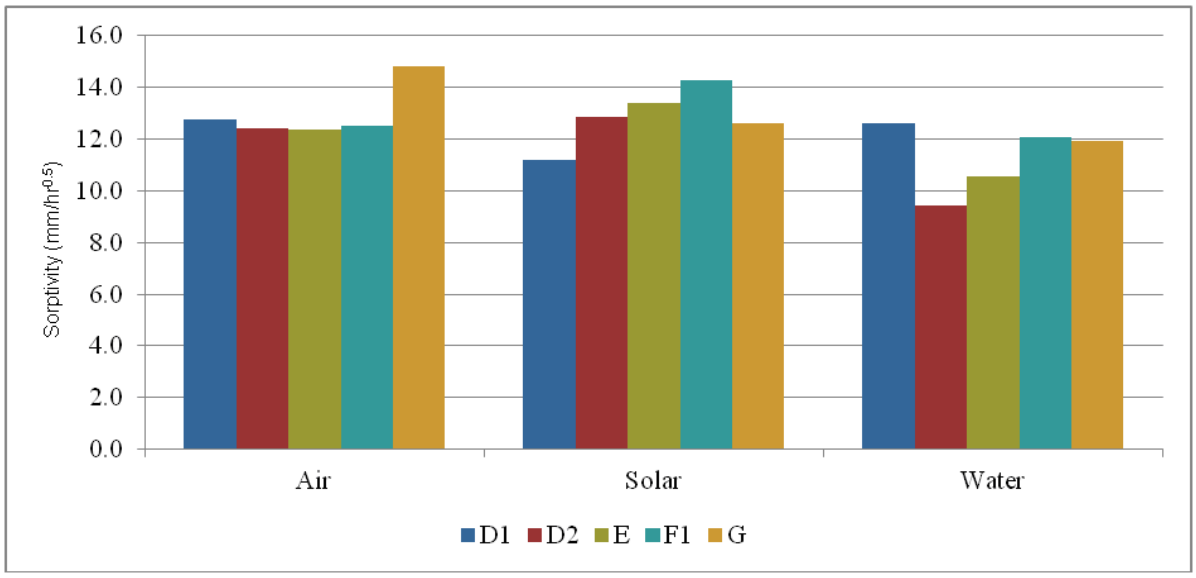


Figure 4.4.3.4—1: Sorptivity of the Class 42.5 Cements

On the whole, similar observations are made with the class 42.5 cements and the class 32.5 cements. Curing in the solar chamber results in similar sorptivity values compared to curing in air. Curing in water shows greater durability compared to curing in air and in the solar chamber.All the cement specimens cured in air, except specimens of cement G shows similar sorptivity results ranging between 12.4 and 12.7 mm/hr$^{0.5}$. The sorptivity of G is 14.8 mm/hr$^{0.5}$.

Specimens cured in the solar chamber show minor variance in the trends noted with specimens cured in air. Cement D1 yields the lowest sorptivity value. 11.2 mm/hr$^{0.5}$ are recorded which is the lowest recorded value. However, the water cured sorptivity values of cement D1 are found to be greater than all the other cements and has a sorptivity value of 12.6. This value shows an unusual result: curing in the solar chamber resulted in superior durability. The finding is considered to be unusual since the water cured specimens of the class 32.5 cements had attained superior durability compared to the solar chamber cured specimens.

The sorptivity of cement G which is recorded to be 12.6 mm/hr$^{0.5}$ yields enhanced durability compared to the sorptivity of cements D2, E and F1 which have sorptivity values of 12.9, 13.4 and 14.3 mm/hr$^{0.5}$ respectively. However, inferior durability is observed for the cement specimens of cement G after being cured in air compared to all the other cements.

Minor variances were also noted for cements D2, E and F. It is expected that the solar chamber sorptivity values would have been slightly less compared to those cured in air. The solar chamber specimens yielded 4.0%, 8.1% and 14.4% greater sorptivity results compared to the specimens cured in air.

4.4.3.5. Observations for the Class 52.5 Cements

Figure 4.4.3.5—1 encapsulates the sorptivity results for the class 52.5 cements.

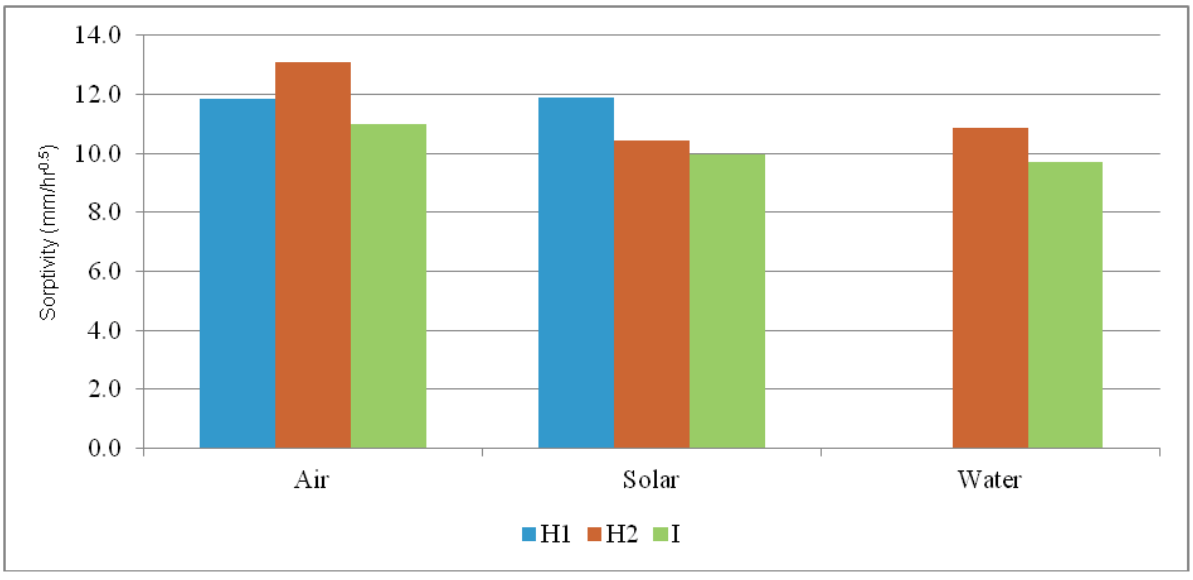


Figure 4.4.3.5—1: Sorptivity Results of 52.5 Cements

No sorptivity results were reported for the water cured specimens of cement H1 owing to damage that resulted to the specimens during the coring operation. However, from the results

of specimens cured in water and the solar chamber, it would be reasonable to suppose that the durability characteristics of cement H1 would have been similar to cement H2.

The results of the sorptivity test for cement H1 showed that the solar chamber yielded the same durability characteristics compared to specimens cured in air. The average sorptivity in both cases was reported to be 11.9 mm/hr$^{0.5}$.

The results of sorptivity of cement H1 compared to cement H2 suggested that the durability characteristics of cement H1 would be slightly better (9.2%) compared to cement H2, however, such a speculation would be questionable since the results of the sorptivity for specimens cured in air showed that cement H1 had a 14.4% greater value of sorptivity. It would be reasonable to induce from the results as well as the discussion on the 32.5 and 42.5 cements that the differences in results were insignificant and showed a minor degree of scatter.

Cement H2 showed an improvement of 2.7 mm/hr$^{0.5}$ or a 20.6% improvement in durability after being cured in the solar chamber compared to specimens cured in air but showed a decrease of 0.5 mm/hr$^{0.5}$ or 3.7% after being cured in air. These findings suggested that there was a minor degree of scatter in the results.

The sorptivity results of cement I for all three curing regimes were similar and revealed that the best curing technique would be continuous moist curing under water (9.7 mm/hr$^{0.5}$) followed by curing in the solar chamber (10 mm/hr$^{0.5}$) and thereafter curing in air (11 mm/hr$^{0.5}$). The findings suggest that curing in the solar chamber compared to curing in water yielded similar durability (3.0% difference) and marginal improvement compared to curing in air (9.1% difference).

4.4.3.6. Implication of the Findings

The variances noted in the observations may be due to a wide range of factors. For instance, with regards to the solar chamber results of cement C, the results would be subject to debate. It was expected that the solar chamber results would be similar or slightly less than those of the specimens cured in air as was noticed for all the other cements. However, the results showed that the solar chamber curing regime resulted in the poorest concrete.

There could be numerous sources of error to explain the variances. The average compaction effort applied might have been less during filling the cubes. As a consequence, certain specimens may have been denser compared to other mixes. This could result in improved

durability.

The specimens could have been damaged in the oven by high temperatures that could have resulted due to faulty temperature regulation. Possibility of micro surface fractures during the cutting operation which could have facilitated greater capillary suction when the specimens were tested for sorptivity. High temperatures to reduce the time for drying discs can lead to damage of the microstructure (Perrie, 1994). However, this reason would be unlikely since it is probable that all the samples were subjected to the same conditions. Fluctuating temperatures and humidity levels over the duration of the curing period is likely to be a significant factor for the discrepancies. Unfortunately, no measurements on humidity and temperature were recorded.

With regards to the sorptivity values recoded for the different cements, it is advantageous to relate the sorptivity results to established limits in order to assess the performance of the various cements. Figure 4.4.3.6—1. provides a measure of the significance of sorptivity ranges.

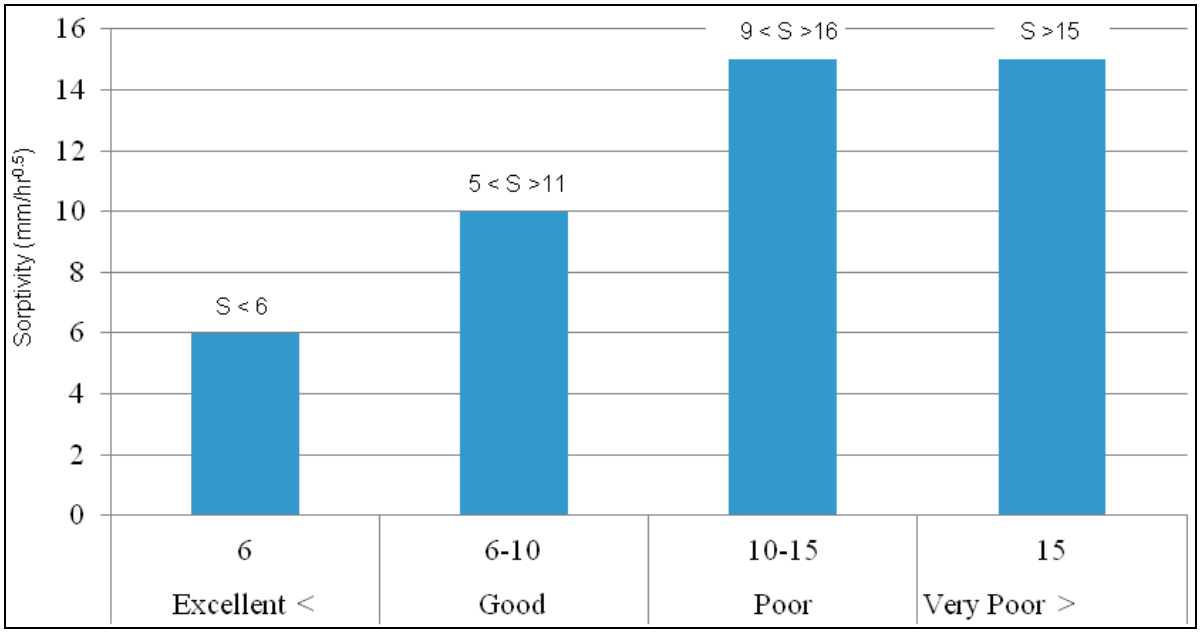


Figure 4.4.3.6—1: Characterisation of Concrete Durability Based on Sorptivity Ranges (From Ikotun, 2009, Table 2.5:52)

Having noted the observations, it could be concluded that the sorptivity results for class 32.5 cement specimens cured in air and in the solar chamber range between 10.6 and 12.5 (sorptivity of solar chamber specimens of cement C is neglected). This range indicates that the various cements would be unsuitable in harsh environments where durability may be an issue as poor concrete typically has a sorptivity range between 10-15 mm/hr$^{0.5}$ respectively.

Curing in water yielded superior concrete compared to specimens cured in air and in the solar chamber. The range of sorptivity values were between 7.7 and 10.4. The lower sorptivity values have demonstrated the practical benefit of continuous moist curing as the range of 6-10 mm/hr$^{0.5}$ indicates good durability performance.

On the whole, the average sorptivity of the specimens cured in air was recorded to be 12.9 mm/hr$^{0.5}$. The solar chamber specimens were found to have an average of 12.1 mm/hr$^{0.5}$ after neglecting cement C specimens. The water cured specimens are found to have a sorptivity of 9.4. Thus, it would be apparent that curing in the solar chamber compared to specimens cured in air showed minor benefit. Water curing instead, shows 22.3% superior durability compared to curing in the solar chamber and 27.1% superior durability compared to specimens cured in air.

From the observations of the class 42.5 cements, it could be concluded that the sorptivity results of specimens cured in water practically indicate the importance of continuous moist curing as the range of the sorptivity values were between 9.4 and 12.6. Air cured sorptivity results varied between 12.4 and 14.4 whereas the solar chamber cured specimens ranged between 11.2 and 14.3 mm/hr$^{0.5}$. Just as with the 32.5 cements, the range of sorptivity results suggested that the mixes would be unsuitable in environments requiring good durability characteristics of concrete.

On the whole, the average sorptivity recorded for the class 42.5 cements cured in air is 13 mm/hr$^{0.5}$ whereas the specimens cured in the solar chamber are found to have a value of 0.8% less or 12.9 mm/hr$^{0.5}$. Curing in water results in superior durability compared to curing in air by 13.1% and compared to the solar chamber by 12.4%. The average sorptivity recorded for specimens cured in water is 11.3 mm/hr$^{0.5}$.

Similar trends of the effects of the three different curing regimes are noticed for the class 52.5 cements. Curing in air results in the least durable concrete specimens whereas curing in water results in superior durability. The average sorptivity is found to be 12 mm/hr$^{0.5}$ for cements cured in air. Cements cured in the solar chamber had resulted in an average of 10.8 mm/hr$^{0.5}$ whereas continuous moist curing in water results in 10.3 mm/hr$^{0.5}$ of sorptivity. In terms of percentage difference, compared to curing in the solar chamber, 4.6% greater durability is noted for specimens cured in water. A greater percentage differences is observed for moist curing in water where 14.2% superior durability prevails compared to specimens cured in air.

4.5. Part Five: Pycnometric Studies

This section comprises two parts. The first part deals with the water absorption of the pycnometers which is referred to as water absorption studies and second part deals with the XRF results.

4.5.1. Water absorption Studies

This chapter of the report is introduced by stating the assumptions and limitations of the study. Speculations are then made on the expected outcomes from the pycnometric studies. The results from the study are presented graphically and the observations are stated. Discrepancies are noted between the observed results and the speculations cited.

A discussion then follows in order to interpret the observations and explain the discrepancies. Finally, implications of the findings are stated. Details of the mix design and methodology are presented in Chapter three, Section five. A review of pycnometric studies is provided in Chapter two, Section five. Appendix 4.3contains the water absorption trends for the different pycnometers.

4.5.1.1. Assumptions and Limitations

Ballim (1989) prepared only one specimen for the different mortar mixes in his study. No reasons were provided for not making at least three specimens for an average. The research project of Fulton (1964) investigated three specimens for the different mixes in order to obtain an average.

The different mixes comprised of cement paste only. It would be advantageous to study a great number of specimens in order to establish statistical reliance. In this research report however, two specimens have been investigated for each mix in order to obtain an average.Ballim (1989) and Fulton (1964) prepared the mixes in their study by hand mixing in a bowl. In the present study, the mixing of the mortar pastes was prepared in an electronic Hobart mixer.

Ballim (1989) and Fulton (1964) manually compacted the mixes in the study by jolting the specimens by hand. In the present study, compaction is ensured using a vibrating table.

Both Ballim (1989) and Fulton (1964) made use of graduated pipettes calibrated to 1ml. In the present study, the pipettes were graduated to 2ml. It is assumed that there would be little difference in using a 2ml pipette instead of a 1ml pipette.

Further assumptions and limitations are detailed appropriately in the next section.

4.5.1.2. Expected Outcomes

In order to predict the water absorption patterns of the various mixes in the present study, it was necessary to review aspects such as moisture, surface area, fly ash, hydration and porosity.

The expectations outlined herein speculate on the water which the pastes might consume.

Speculation One:

Accelerated hydration can be achieved through making use of cement with greater degrees of surface area. A large surface promotes greater contact with water for hydration to occur (Lin & Meyer, 2009).

In the present study, it is assumed that the class 52.5 cements had the greatest surface area. It is also assumed that the class 32.5 cement had the smallest surface area. In turn, the class 42.5 cement had a surface area that ranges between the class 52.5 and class 32.5 cements.

The consequence of the assumption is that the class 52.5 cement would be the most reactive and would hydrate the fastest. That is, this cement would achieve high early strength characteristics which would be manifested in terms of large water absorption characteristics.

On the contrary, the class 32.5 cement would hydrate the slowest. This would be manifested in terms of low water absorption characteristics and low strength development.

The class 42.5 cement hydration characteristics would be in between those of the class 32.5 and class 52.5 cements.

The water consumed in the early stages (under three days at least) by the mixes belonging to the class 52.5 cement are expected to be greater than the mixes belonging to the class 42.5 and class 32.5 cements due to the assumed large surface area and high reactivity associated with the class 52.5 cement.

In the long term (after seven days at least), it is expected that the water consumed by the class 32.5 cement might be greater than the class 42.5 and class 52.5 cement due to the low surface area assumed to be associated with this class of cement. This is because the rate of hydration would be slower and strength development would take a longer period.

Speculation 2:

Fly ash has the effect of improving workability in general. However, the consequence of increased contents of fly ash is reduced rate of strength development (Fulton, 1964).

From this note, it is speculated that the control mixes would hydrate to a greater extent compared to the fly ash mixes. Furthermore, it is speculated that the 30% fly ash mix would hydrate the least. In turn, the hydration of the 15% fly ash mix would be inbetween the control and the 30% fly ash mix.

The speculation would be manifest in terms of the total water absorbed by the different mixes. For each group of cements, the control mix should absorb the most water whereas the 30% fly ash mix would absorb the least amount of water. The 15% fly ash mix would absorb more water than the 30% fly ash mix but less water than the control mix providing that the speculation is correct.

4.5.1.3. Water Absorption Characteristics of Pycnometer Mixes

The water absorption patterns for three, seven and twenty eight days shown in Figure 4.5.1.3—1 through to Figure 4.5.1.3—3 are presented as a fraction of the total water recorded after twenty eight days of hydration. The following relationship provides clarity:

$$\%\ Water\ Absorbed = \frac{Water\ Consumed\ at\ Period\ t\ (ml)}{Total\ water\ Consumed\ at\ 28 Days\ \ (ml)} \times 100$$

It should be mentioned that the results are ‘’adjusted and reported in percentage form by taking the volume of water absorbed after 28 days as a base and so, the volume after 28 days would be 100%. This must not be misinterpreted as being the actual amount of water absorbed after 28 days.

The next two sections outlines the observations made on the water absorption characteristics for the different mixes and is separated into two parts. The first part presents the results into three groups and seeks to test the first speculation. The second part presents the results of each class of cement collectively and seeks to test the second speculation.

4.5.1.4. Observations on Water Absorption Characteristics: Testing the First Speculation

In this section of the report, the first speculation is tested.

The report is organised such that the results of the control mixes are first introduced. Thereafter the results of the fifteen percent fly ash mixes and finally the results of the thirty percent fly ash mixes.

Figure 4.5.1.4—1 shows the water absorption characteristics of the control mixes of the three cements.

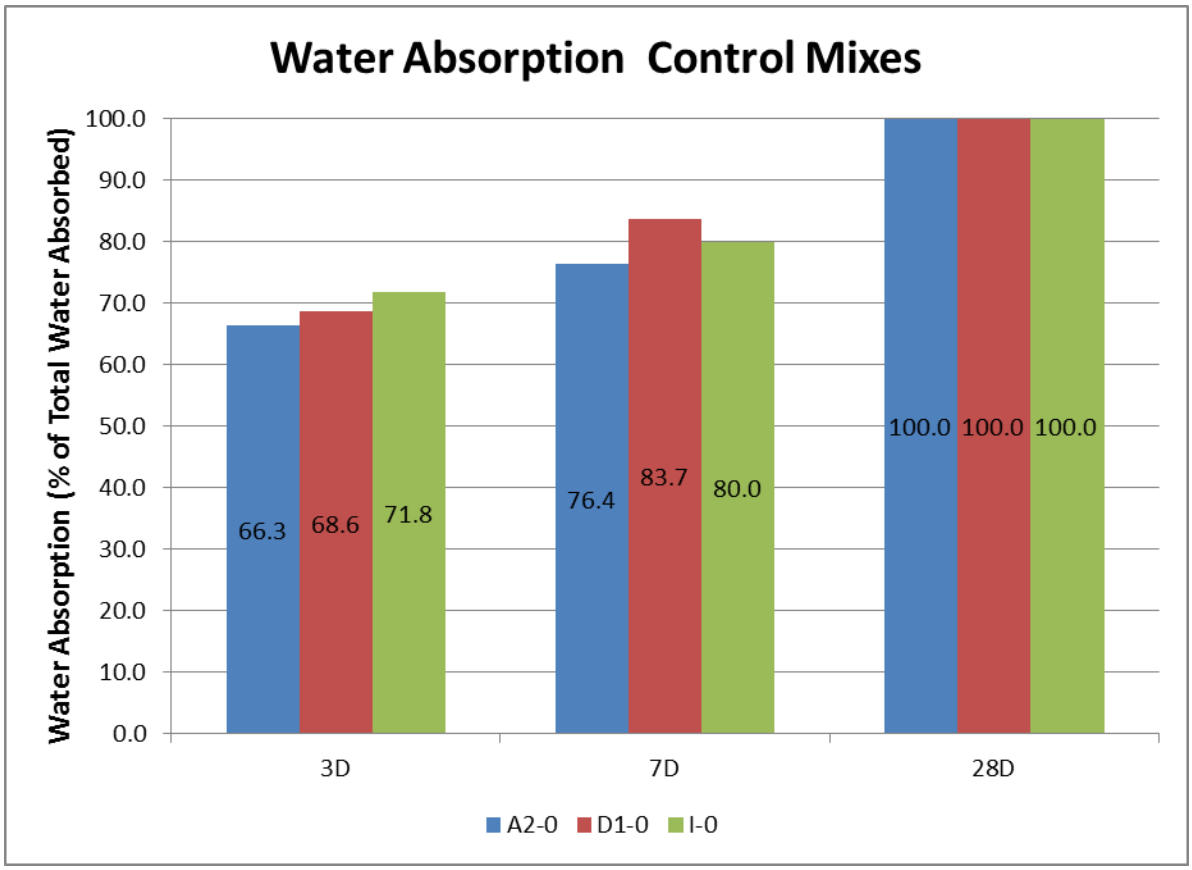


Figure 4.5.1.4—1: Water Absorption Characteristics of the Control Mixes Relative to the 28 Day Measurements

After three days of hydration, it is noticed that the class 52.5 cement absorbed the greatest amount of water compared to the class 42.5 and class 32.5 cements. The amount of water absorbed by the class 52.5 cement after three days of hydration is 71.8%. The amount of water absorbed by the class 42.5 cement is 68.6% and the amount of water absorbed by the class 32.5 cement is 66.3%.

It was speculated that the class 52.5 cement would absorb the greatest amount of water compared to the class 32.5 and class 42.5 cements. This speculation is confirmed for the three day results.

However, it should be mentioned that the differences between the quantities of water absorbed appears to be minor. The class 42.5 cement absorbs 3.2% less water compared to the class 52.5 cement whereas the class 32.5 cement absorbs 5.5% less water compared to the class 52.5 cement.

At seven days of hydration, the trend shows that the class 42.5 cement hydrates to the greatest degree compared to the other two cements, namely the class 32.5 and class 52.5 cement.

However, the water absorption percentage between the class 42.5 and class 52.5 cement is found to be 3.7%. If this difference could be considered to be insignificant, it would imply that the class 42.5 and class 52.5 cement have similar hydration characteristics.

Figure 4.5.1.4—2 shows the water absorption characteristics of the fifteen percent fly ash mixes

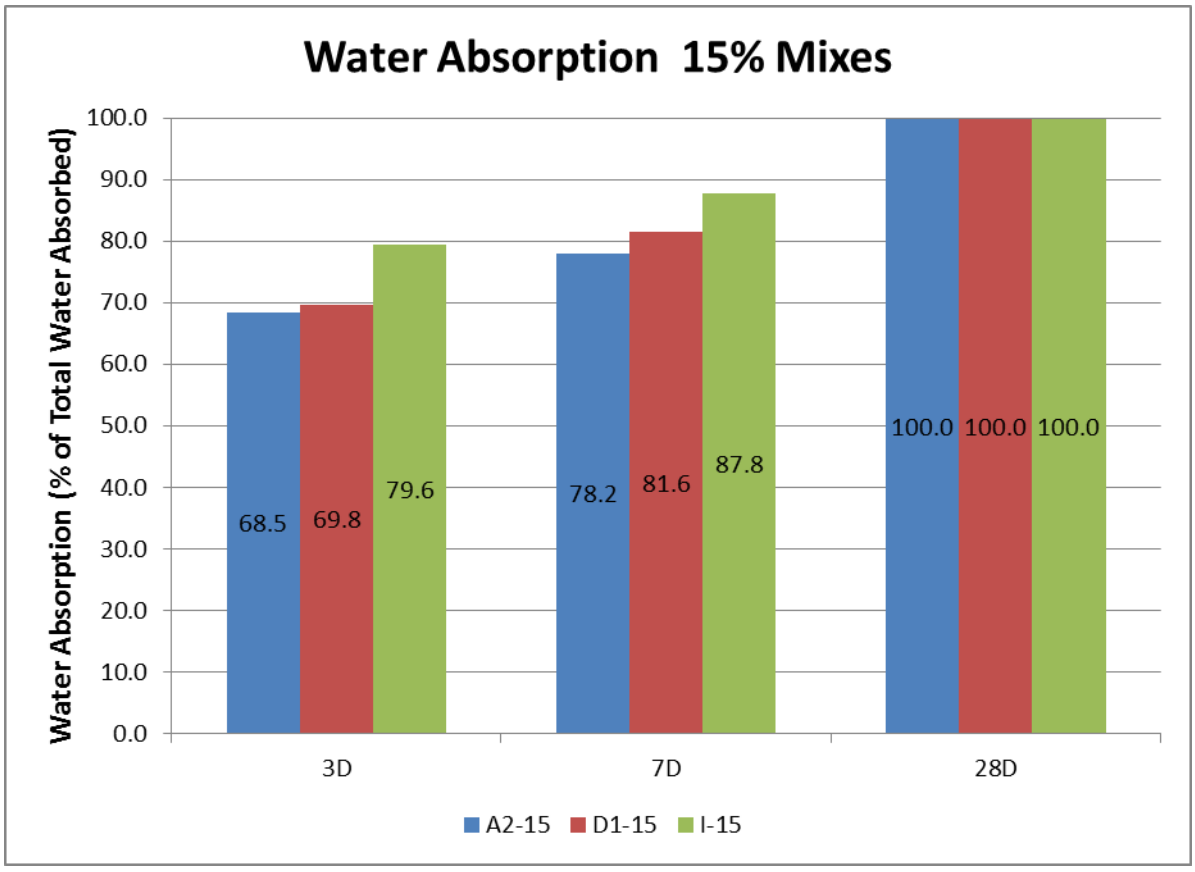


Figure 4.5.1.4—2: Water Absorption Characteristics of the 15% Fly Ash Mixes Relative to the 28 Day Measurements

With regards to the fifteen percent fly ash mixes, it was speculated that mixes blended with the class 52.5 cement would hydrate the most whereas the mixes blended with the class 32.5 cement would hydrate the least. Furthermore, it was speculated that the fly ash blend of the class 42.5 cement would hydrate to an extent greater than the class 32.5 cement but less than the class 52.5 cement.

The above speculation is confirmed as shown in Figure 4.5.1.4—2. The fly ash blend belonging to the class 52.5 cement, namely mix I-15, consumed the greatest quantity of water. The mortar mix which consumed the least water is A1-15 which belongs to the class 32.5 cement. The blended fly ash mix belonging to the class 42.5 cement consumed more water than the class 32.5 cement but less water than the class 52.5 cement.

The above observations are true at three and seven days.

After three days of hydration, 68.5% of hydration was complete for the class 32.5 mix, 69.8% for the class 42.5 mix and 79.6% for the class 52.5 mix.

After seven days of hydration, 78.2% of hydration was complete for the class 32.5 mix, 81.6% for the class 42.5 mix and 87.8% for the class 52.5 mix.

The results for the thirty percent fly ash mixes for each cement class are presented in Figure 4.5.1.4—3

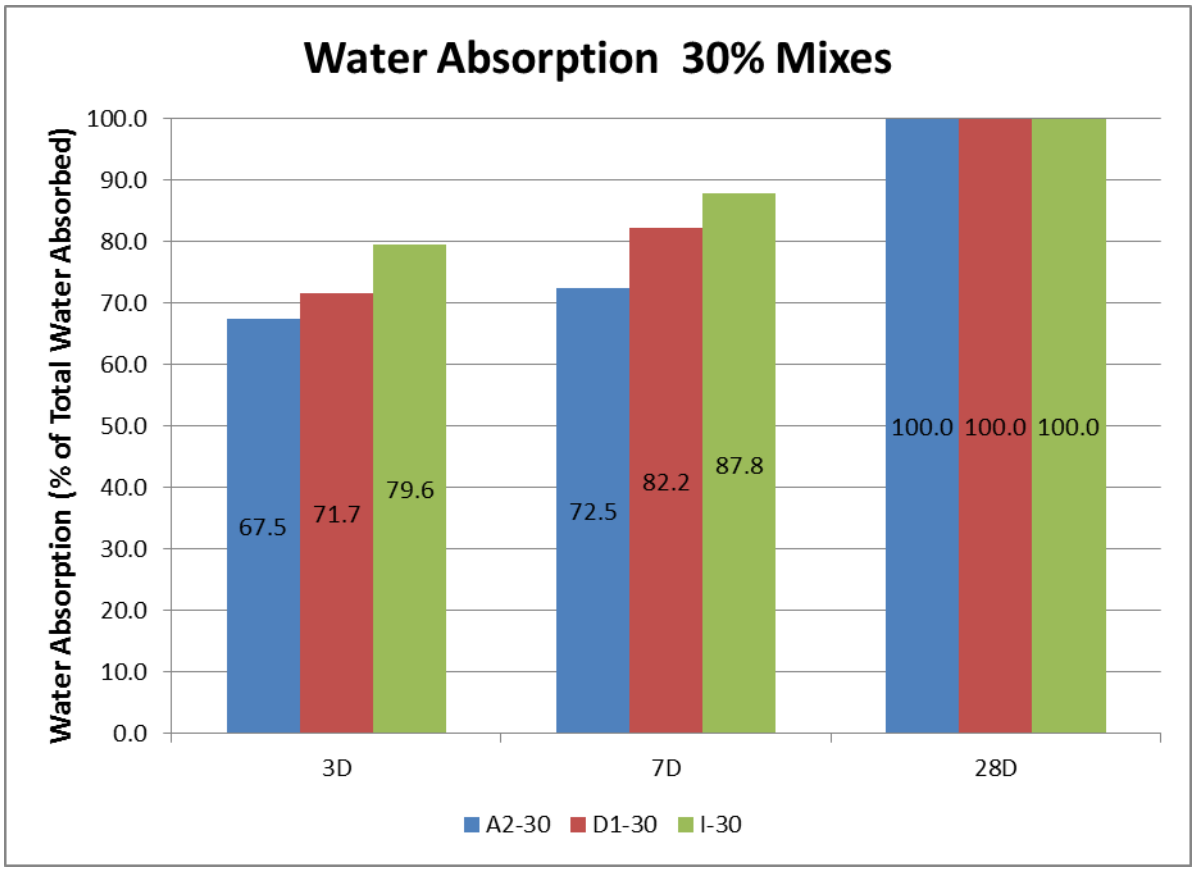


Figure 4.5.1.4—3: Water Absorption Characteristics of the 30% Fly Ash Mixes Relative to the 28 Day Measurements

It was speculated that the mixes belonging to the class 52.5 cement would hydrate to a greater extent compared to the class 42.5 and class 32.5 cement. It was also speculated that the mixes belonging to the class 32.5 cement would hydrate the least. In turn, the aforementioned speculations imply that the mixes belonging to the class 42.5 cement would show hydration characteristics which are in between the class 32.5 and class 52.5 mixes.

This speculation is confirmed at three and seven days through the water absorption characteristics shown in Figure 4.5.1.4—3.

The degree of hydration experienced by the class 52.5 mix, given by label I-30, was 79.6% after three days and 87.8% after seven days. The class 32.5 mix experienced the least degree of hydration at three and seven days with 67.5% and 72.5% recorded. The class 42.5 blend experienced 71.7% after three days and 82.2% after seven days which shows hydration characteristics in between the class 32.5 and class 52.5 mix as expected.

From the Results presented in Figures 4.5.1.4—1 to 4.5.1.4—3, the speculations outlined in the previous section have been satisfied. The results appear to indicate that the pycnometers are a useful means of inferring the extent of and degree of hydration for different mixes.

However, the next section shows that the pycnometers may not necessarily be a useful technique. Further commentary is presented in the next section.

4.5.1.5. Observations on Water Absorption Characteristics: Testing the Second Speculation

The previous section confirmed the first speculation that the class 52.5 mixes would hydrate to a greater extent compared to the class 32.5 and class 42.5 mixes. The previous section also confirmed that the class 32.5 mixes hydrated the least whereas the hydration characteristics of the class 42.5 mixes were in between those of the class 32.5 and class 52.5 mixes.

The second speculation dictates that the control mixes would hydrate to a greater extent compared to the fifteen and thirty percent fly ash blends. Furthermore, the thirty percent fly ash blend would hydrate the least.

The results are organised such that the water absorption characteristics after three, seven and twenty eight days are presented separately for each mix. It should be mentioned that the water absorption trends for the three and seven day results are in percentage form relative to the

Figure 4.5.1.5—1 shows the water absorption characteristics after three days.

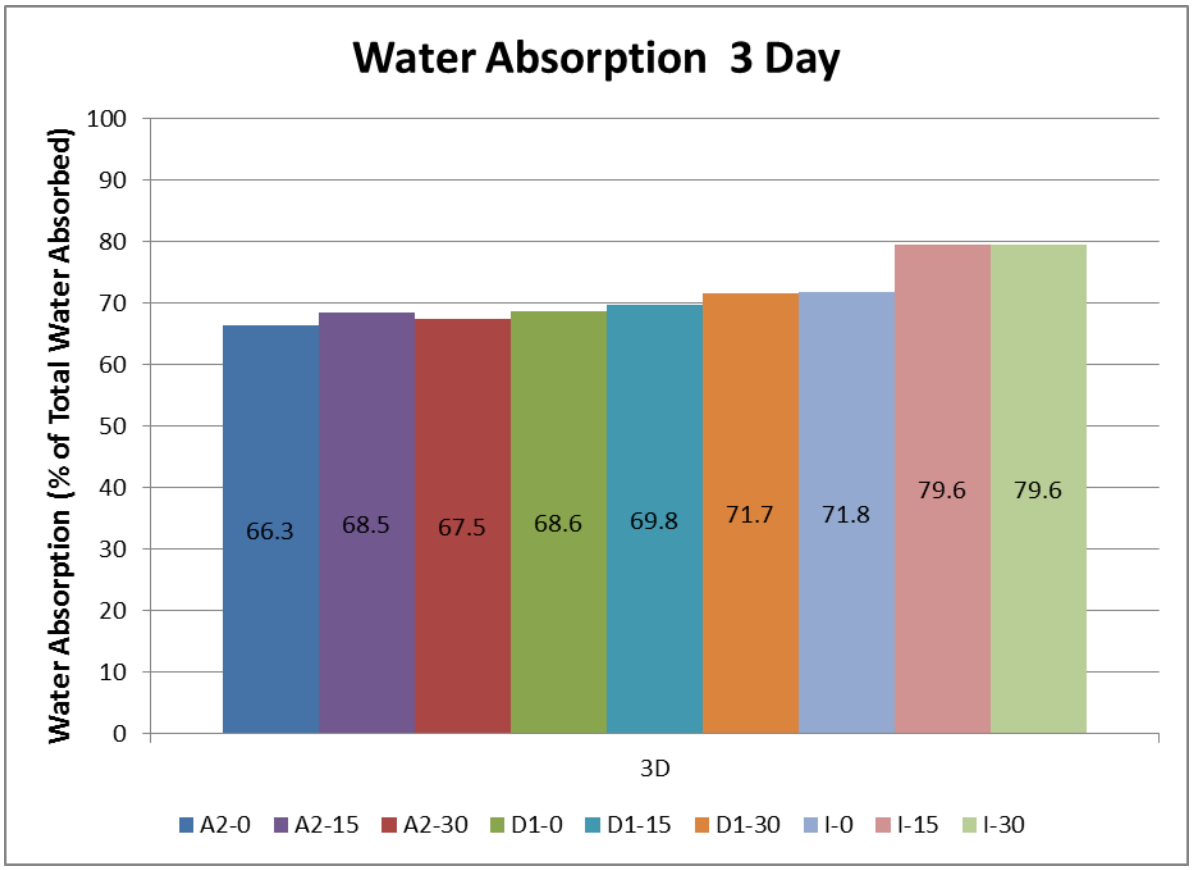


Figure 4.5.1.5—1: Water Absorption Characteristics after 3 Days

From Figure 4.5.1.5—1, it is evident that there is no clear trend that establishes which mix (control, fifteen percent fly ash or thirty percent fly ash mix) hydrates to the greatest extent.

For mix A, the fifteen percent mix shows the greatest hydration with 68.5% recorded. For mix D, the thirty percent mix shows the greatest hydration whereby 69.8% was noted. For mix I, the fifteen and thirty percent mixes achieved the greatest hydration with 79.6% observed.

The results shown in Figure 4.5.1.5—2 which are the seven day results show further discrepancies

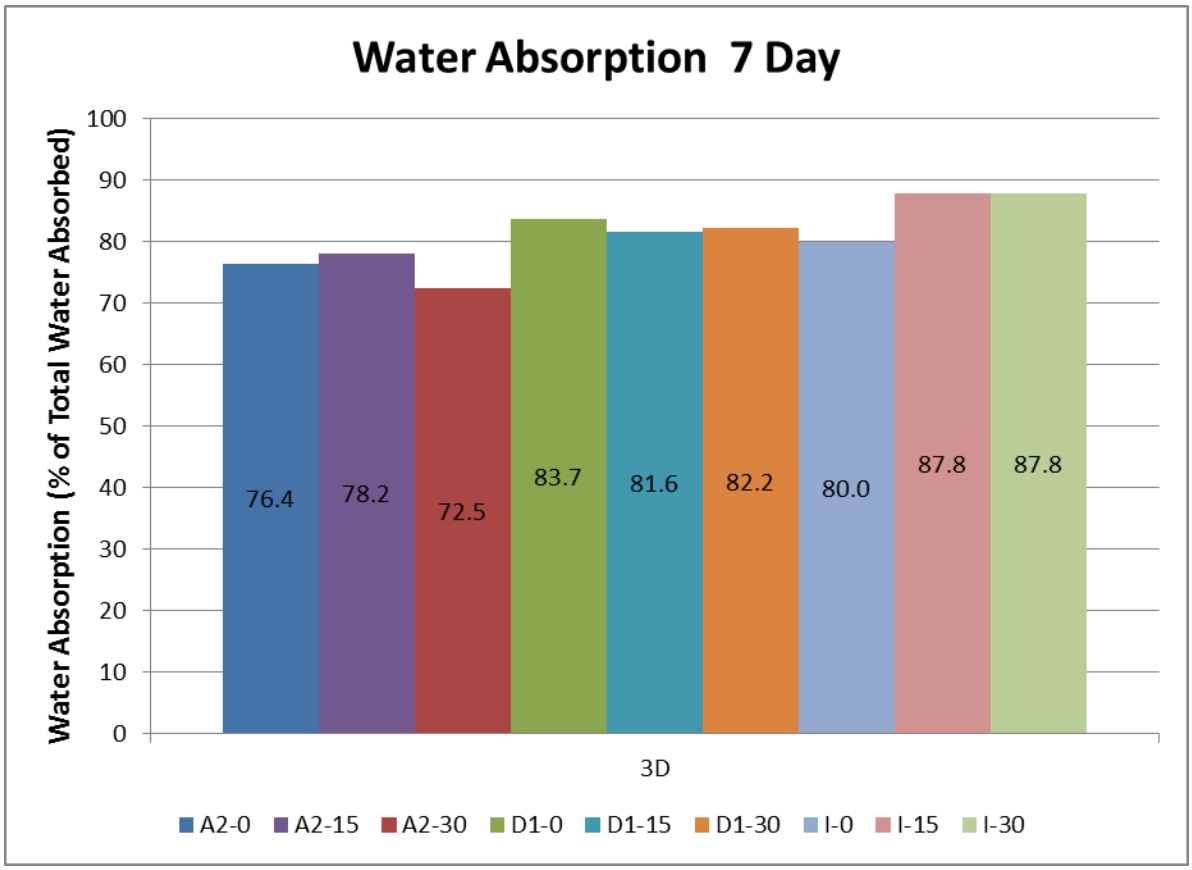


Figure 4.5.1.5—2: Water Absorption Characteristics after 7 Days

At seven days, the thirty percent fly ash blend of mix A experiences the least hydration compared to the fifteen percent blend and the control where 72.5% is observed. This is in contrast to the three day readings where the control mix experienced the least degree of hydration.

With regards to mix D, the control is found to experience the greatest degree of hydration with 83.7% recorded. However, the control mix at three days for mix D actually experienced the least extent of hydration compared to the fifteen and thirty percent fly ash blends.With regards to mix I, there is a discrepancy. The three fifteen percent mix and thirty percent mix absorb the same percentage.

Figure 4.5.1.5—3 shows the total water consumed per gram of cement after allowing for twenty eight days of hydration. The following relationship is used:

$$Tot\ Water\ Consumed\ \left(\frac{ml}{g}\right) = \frac{Water\ Reading\ At\ 28Days\ (ml)}{Mass\ of\ Mortar\ in\ Pycnometer\ (g)}$$

Figure 4.5.1.5—3 is used presented in ml/g for comparative purposes. Not all the pycnometers had exactly the same amount of mortar. Thus, in order for sensible conclusions to be drawn, it is sensible to compare the water consumed per gram of cement.

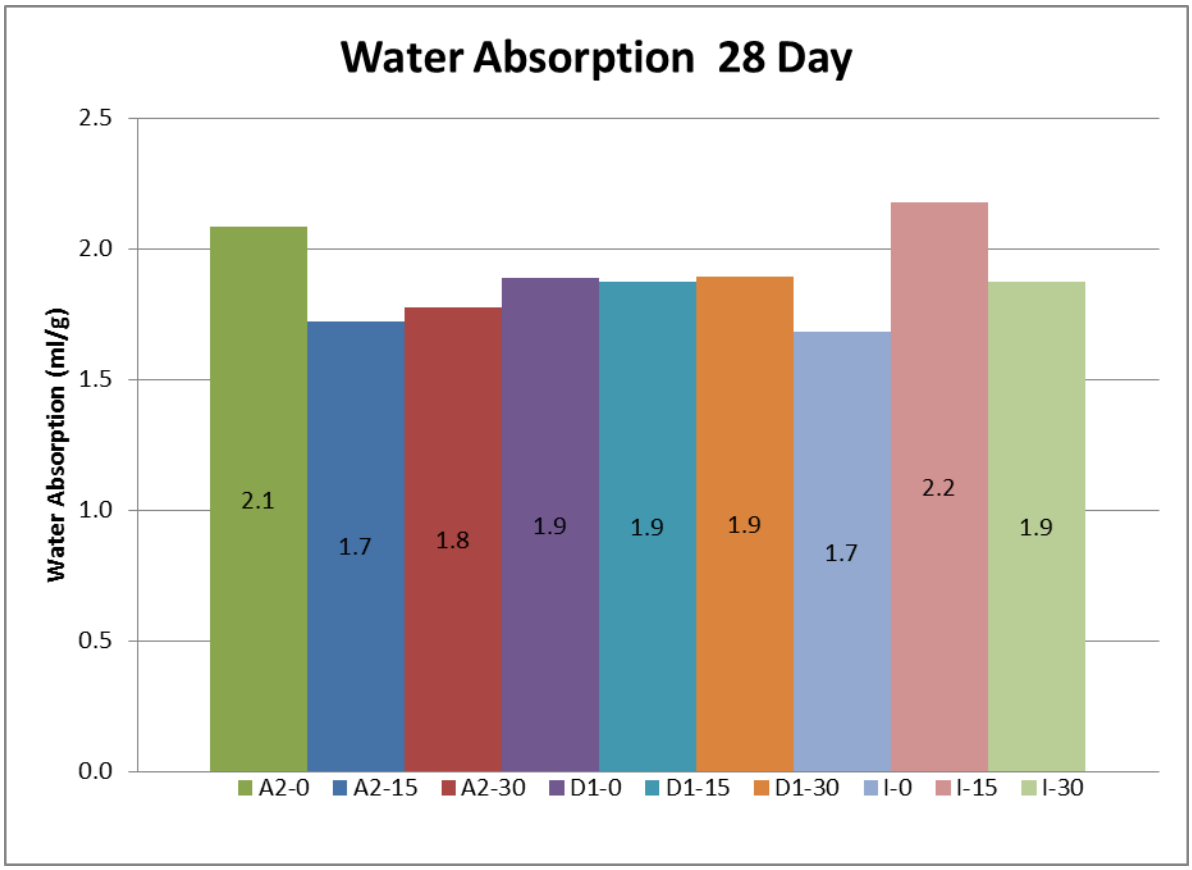


Figure 4.5.1.5—3: Water Absorption Characteristics after 28 Days

Unfortunately, the trends between the three classes of cements are not consistent.

With Mix A1, the control is found to have absorbed the greatest quantity of water. With mix D1, all three blends show the same ultimate water absorption characteristics. For mix I, the fifteen percent fly ash mix is found to have absorbed the greatest quantity of water.

4.5.1.6. Implications of Findings

It was noted that the trends in water absorption were not consistent between the three periods at which measurements were taken.

After considering the water absorption readings, it was decided that the inconsistency of the readings observed could have been attributed to the following:

(a) The accuracy which the mortar pastes absorbed water was recorded to an accuracy of 0.2 ml. The quantity of water absorbed at different periods could be considered to be small.

To explain the effect of the tolerance level to which the water levels were recorded, mix A1-0 is discussed:

The average reading of water consumption for mix A1-0 was 6.2ml at three days. Since the water levels were recorded to an accuracy of 0.2ml, it would imply that the reading could vary between 6.0ml and 6.4ml. The total water consumed for mix A1-0 was 9.5ml.

Thus, if the lower limit of 6.0ml is used to determine the degree of total hydration of the third day's readings in relation to the twenty eighth day readings, 63.2% is obtained. If the upper limit of 6.4ml is used instead, 67.4% is obtained. The results for this case between using the upper and lower limit vary by 4.2%.

Since the differences between the amounts of water absorbed between the mixes were similar, and since the water consumed between the different periods could be considered to be small, the tolerance level 0.2ml could be considered to be undesirable to distinguish minute differences in hydration. However, this speculation would require further investigation.

(b) The water absorption of the pastes could be affected by the manner in which the mortar for the pycnometers was prepared. There could have been an uneven distribution of cement, fly ash, sand and water between the different pycnometers. The uneven proportion of material could have roused from improper mixing. If the proportions of material in the pycnometers contained more than one type of material compared to the other, the water absorption would naturally be different.

(c) When the mortar pastes were added to the pycnometers and compacted, the amount of compaction effort could have possibly been different between the different mixes. If this speculation is correct, it would possibly imply that the specimens which had been compacted more properly would have absorbed less water than the specimens which were less properly compacted. Greater compaction effort could result in a denser structure associated which could limit the ingress of moisture and in turn water absorption of the mortar pastes.

(d) When the mortar pastes were being filled with water after being compacted, surface damage of the pastes may have resulted as the fresh state of mortar can be easily worked. It is possible that a damaged surface would allow for water to penetrate more easily into the rest of the mortar than a mortar mix whose surface had been unspoiled.

In conclusion, the water absorption characteristics of the mixes in this study would require further investigation to establish reasons for the variability outlined. Nonetheless, the

Pycnometer apparatus appears to be a useful technique to infer the degree and rate of hydration.

4.5.2. X-Ray Fluorescence (XRF) Analysis

Motivation for conducting XRF analysis on samples before and after hydration was inspired by Sisomphon (2009). In chapter one, under Section 1.3, an outline was presented on the work of Sisomphon which prompted an investigation into whether or not XRF could be used to infer the degree of hydration or not.

XRF analysis was conducted on nine different fly ash mixes. Section five of Chapter three presents the methodology used to conduct the XRF analysis and outlines the different mixes.

The XRF analysis for all the fly ash mixes is not presented in this section of the report. Only one sample of the fly ash mixes is presented, namely mix A2-15. The conclusions drawn from the fly ash sample presented herein are general in nature and would be applicable to the other fly ash mixes. The results for all other fly ash specimens have been supplemented in Appendix Five.

This section of the report is separated into five parts. Part one introduces the assumptions, limitations and expectations of the study. Part two deals with the XRF results on the fly ash mix prior to hydration. Part three delves into comparing the XRF results before and after hydration. Part four deliberates on the implications of the findings.

Appendix 4.4 contains the XRF results.

4.5.2.1. Part One: Assumptions, Limitations and Expectations

The study is limited to investigating three types of commercial grades of cement blended with two proportions of fly ash. The proportions investigated are fifteen and thirty percent fly ash replacement of cement by weight.

The first type of cement contains 21-35% fly ash. This cement is classified as a pozzolanic cement and has repid gaining strength characteristics. The chemical notion ascribed to the cement follows: CEM IV/B-V 32,5R.

The second type of cement contains between 6-20% fly ash and limestone, belongs to the Portland composite cement group and has normal gaining strength characteristics. This cement categorized with the class 42.5 group of cements and has the following chemical notion: CEM II/A-M (V-L) 42,5N.

The third type of cement contains between 6-20% fly ash, belongs to the Portland composite group and has normal gaining strength characteristics. This cement belongs to the class 52.5 group of cement and the chemical notion associated with this cement is CEM II/A-V 52,5N.

The exact quantity of extender present in these three different types of cements is unknown. Furthermore, the exact nature of the fly ash and limestone are not known nor is the geological source of the materials known.

However, these limitations are not significant as an XRF analysis was conducted for all of the fly ash mortar mixes in the dry state prior to hydration in order to determine the elemental composition of the mixes.

XRF analysis was conducted on the mixes in a dry state prior to hydration and after twenty eight days of hydration. It was not deemed necessary to conduct XRF analysis over extended periods. The outcome after twenty eight days of hydration would be sufficient to infer whether the XRF technique is useful or not to infer the degree of hydration.

A single sample for each of the mixes was analysed for XRF. For greater statistical reliability, a greater number of specimens would be desirable to study.

With regards to the expectations of the study, there are two aspects that were expected.

The first aspect deals with what was to be expected between the measured XRF results on hydrated samples and the theoretically determined XRF results: It was expected that the theoretical results on the materials in the dry state would be closely related to the measured results. The basis for this speculation is because the materials were assumed to be thoroughly homogenised during sampling for XRF analysis.

The second aspect deals with whether XRF can be used to predict hydration or not. In this regard, the XRF results prior to hydration are compared to the XRF results after hydration. The parameters that are investigated are Calcium, Silicon, Aluminium and Sulphur oxide.

It was expected that after comparing the oxides obtained after twenty eight days of hydration to the oxides prior to hydration, Calcium and Sulphur oxide would show an increase whereas the contents of Silicon and Aluminium oxide would show a decrease. Motivation for these expectations have already been outlined in Chapter One.

4.5.2.2. Part Two: XRF Results Prior to hydration

The un-hydrated XRF results of mix A2-15 are presented herein into four separate parts. The first part deals with how the theoretical XRF results were determined. The second part

presents the measured XRF results. The third part compares the measured XRF results to the theoretically determined XRF results. The fourth part concludes with implication of these findings and how these findings could affect the next portion of the study involving the results of mix A2-15 after allowing for twenty eight days of hydration.

4.5.2.2.1. Theoretical XRF Results

Table 4.5.2.2.1-1 shows the XRF analysis conducted on the individual materials that contribute towards mix A2 for each of the different materials such as the fly ash, sand and cement. There are different columns in the table which are explained hereunder that deal with presenting the theoretical XRF results of mix A2-15.

	1	2	3	4	5	6	7	8
1	OXIDE (%)	FLY ASH	SAND	CEMENT	A	B	C	D
2	SiO_2	53.97	54.25	32.08	44.81	44.82	44.81	45.77
3	Al_2O_3	33.45	14.02	14.41	15.64	15.65	15.64	15.98
4	Fe_2O_3	3.45	12.57	3.19	7.90	7.90	7.90	8.07
5	CaO	4.41	7.61	42.22	22.08	22.09	22.08	22.56
6	MgO	1.11	4.46	1.48	2.94	2.94	2.94	3.01
7	K_2O	0.66	1.04	0.32	0.71	0.71	0.71	0.72
8	Na_2O	0.19	3.33	0.10	1.72	1.72	1.72	1.76
9	TiO_2	1.57	0.85	0.92	0.93	0.93	0.93	0.95
10	Mn_2O_3	0.04	0.18	0.12	0.14	0.14	0.14	0.15
11	P_2O_5	0.45	0.11	0.23	0.19	0.19	0.19	0.19
12	SrO	0.11	0.03	0.06	0.05	0.05	0.05	0.05
13	SO_3	0.21	0.00	1.79	0.78	0.78	0.78	0.79

14	LOI	0.41	1.74	2.76	2.07	2.07		
15	SUM	100.03	100.19	99.68	99.96	100.00	97.89	100.00
16	A: XRF COMBINED THEORETICAL							
17	B: XRF COMBINED THEORETICAL, NORMALISED TO 100%							
18	C: XRF COMBINED THEORETICAL, EXCLUDING LOI							
19	D: XRF COMBINED THEORETICAL, EXCLUDING LOI, NORMALISED TO 100%							

Table 4.5.2.2.1-2: Theoretical XRF Results for mix A2-15 at 0 Days

Table 4.5.2.2.1-3 has nineteen rows and eight columns to make it easy to refer to different items.

Column one outlines the different oxides that were determined. Columns two, three and four presents the individual XRF analysis of the fly ash, sand and cement correspondingly.

Column five, six, seven and eight show different ways in which the theoretical XRF are determined. The reason for presenting these columns is because these oxide results used to compare the oxide results after twenty eight days of hydration in order to establish whether there would be differences so that the extent of hydration can be predicted or not. An explanation on how the different columns are obtained follows:

Columns five shows the oxide results for the combined sand, fly ash, and mortar mix of A2-15. Mix A2 contains one part sand to one part cementitious material. The cementitious material consists of 85% cement and 15% fly ash. All the material was blended by weight.

To make clear on how the results shown in column five were obtained, the value in the cell of column five, row two is selected to explain:

The mix consists of one part sand to one part cementitious material by weight. The sand content (column three, row two) is multiplied by 0.5 and the cementitious material content (cement and fly ash) is also multiplied by 0.5. This is to account for the equal proportion of sand to cementitious material, hence the factors of 0.5. To explain further, if the proportion consisted of 3 parts sand to 1 part cementitious material, factors of 0.25 and 0.75 would have been used instead.

The cementitious material content has to account for the proportion of fly ash and cement. The fly ash content (column two, row two) is multiplied by 0.15 to account for the 15% fly

ash proportion. The cement content (column four, row two) is multiplied by 0.85 in order to account for the cement content of 85%. Thereafter, both these values are then added to the corrected content of cement in the mix. In equation form, the outcome has been reproduced for clarity below:

$$0.5 \times (52.25) + 0.5 \times [0.15 \times 53.97 + 0.85 \times 32.08] = 44.81\%$$

The cell of column five of row fifteen shows that the total oxide content amounts to 99.96%. The fact that the oxide contents do not amount to 100% could imply that there would be a certain degree of error in comparing oxides contents between samples.

For this reason, all the oxide contents are normalised. Column six encapsulats the normalised oxide contents.

The normalisation procedure simply involves recalculation of each individual oxide content (column one) as a percentage of the total sum of the oxides.

To make clear on how the normalised oxides are obtained, the following equation is used:

$$Normalised\ oxide\ content = \frac{Actual\ Oxide\ Content}{Total\ Oxide\ Content} \times 100$$

For further clarity, consider the cell in column five, row two which is the actual oxide content of Silicon for the combined mix and is given as 44.81%. This would be the numerator value in the above equation

Column five, row fifteen which is the total of the oxides for the combined mix is given as 99.96%. This would be fitted into the denominator of the above equation.

The outcome of applying the numerator and denominator values into the above equation yields the value shown in column six, row two which is the normalised oxide of the silica obtained to be 44.82%.

The cells of columns seven and eight of row fourteen do not contain any numerical value. In column seven, the oxide contents have been presented but exclude the loss on ignition value. Column eight simply shows the oxide contents of column seven normalised to 100%.

The purpose of excluding the loss on ignition contents is for comparison purposes. The oxide contents prior to the onset of hydration and at twenty eight days appeared to be affected by the loss on ignition results. Thus, the results presented in columns seven and eight have been compiled to illustrate this argument later in the report.

4.5.2.2.2. Experimental XRF Results

Table 4.5.2.3—1shows that measured XRF analysis for mix A2-15.

	1	2	3	4	5
1	OXIDE (%)	A2	B2	C2	D2
2	SiO_2	32.08	32.18	32.08	33.10
3	Al_2O_3	14.41	14.46	14.41	14.87
4	Fe_2O_3	3.19	3.20	3.19	3.29
5	CaO	42.22	42.36	42.22	43.56
6	MgO	1.48	1.48	1.48	1.53
7	K_2O	0.32	0.32	0.32	0.33
8	Na_2O	0.10	0.10	0.10	0.10
9	TiO_2	0.92	0.92	0.92	0.95
10	Mn_2O_3	0.12	0.12	0.12	0.12
11	P_2O_5	0.23	0.23	0.23	0.24
12	SrO	0.06	0.06	0.06	0.06
13	SO_3	1.79	1.80	1.79	1.85
14	LOI	2.76	2.77		
15	SUM	99.68	100.00	96.92	100.00
16	A: XRF EXPERIMENTAL RESULTS DAY ZERO				
17	B: XRF COMBINED EXPERIMENTAL ZERO TO 100%				
18	C: XRF COMBINED EXPERIMENTAL EXCLUDING LOI				
19	D: XRF COMBINED EXPERIMENTAL EXCLUDING LOI, ZERO TO 100%				

Table 4.5.2.2.2-1: Experimental XRF Results for mix A2 at 0 Days

Columns two, three, four and five present the measured XRF results in four different ways. Motivation for presenting the results in these four different ways has already been given in the previous section.

The results shown in column one are the actual recorded values obtained from conducting an XRF on the actual composite mixture of A2-15.

The results shown in column two have been normalised so that the grand total of the oxides sum up to 100%. Also, the results shown in column four have been normalised. An explanation of how the results have been normalised has already been explained in the previous section.

Columns three and four present to results without the loss on ignition values.

4.5.2.2.3. Analysis of the Theoretical and Experimental XRF Results

The purpose of comparing the measured oxide contents to the theoretically determined oxide contents of the previous two sections is to establish whether there are any discrepancies between the two techniques.

It was expected that the theoretical results on the materials in the dry state would be closely related to the measured results. The basis for this speculation is because the materials were assumed to be thoroughly homogenised during sampling for XRF analysis. A comparison is conducted in this section in order to make sure of the aspect. Table 4.5.2.2.3—1 shows the outcome of the comparison.

	1	2	3	4	5
1	OXIDE (%)	PERCENTAGE DIFFERENCES COMPARED TO EXPERIMENTAL RESULTS			
2		A	B	C	D
3	SiO_2	-39.67	-39.28	-39.67	-38.29
4	Al_2O_3	-8.56	-8.25	-8.56	-7.48
5	Fe_2O_3	-147.63	-146.94	-147.63	-145.19
6	CaO	47.70	47.85	47.70	48.22
7	MgO	-98.80	-98.24	-98.80	-96.84
8	K_2O	-120.47	-119.85	-120.47	-118.29
9	Na_2O	-1621.75	-1616.91	-1621.75	-1604.73
10	TiO_2	-1.49	-1.21	-1.49	-0.49

11	Mn_2O_3	-20.00	-19.66	-20.00	-18.81
12	P_2O_5	18.91	19.14	18.91	19.71
13	SrO	18.75	18.98	18.75	19.55
14	SO_3	56.62	56.74	56.62	57.05
15	LOI	24.86	25.08		
16	SUM	-0.28			
17	A: $\frac{(A2 - A1)}{A2} \times 100\%$				
18	B: $\frac{(B2 - B1)}{B2} \times 100\%$				
19	C: $\frac{(C2 - C1)}{C2} \times 100\%$				
20	D: $\frac{(D2 - D1)}{D2} \times 100\%$				

Table 4.5.2.2.3-1: Comparison of Experimental to Theoretical XRF Results for mix A2 at 0 Days

Columns two to five show the comparison of the measured and theoretically calculated oxides in four different ways. Column two compares the actual oxides. Column three compares the oxides after normalising the quantities so that the contents have a total of 100%. Column three compares the oxides but neglects the loss on ignition value. Column five does the same except that the oxide contents are normalised to 100%.

For all four of the different ways in which the oxides are compared, it is noticed that on the whole, a large discrepancy is noted between the theoretically calculated oxide contents and the measured oxides.

To motivate the observation, the oxides which show lower measured results compared to the theoretical results are documented and thereafter the oxides which revealed higher oxide contents are noted.

Column three shows the results after being normalised. It is apparent that the results of column three show a marginal difference compared to column two. For instance, most of the percentage differences in oxide contents of column two give similar results to the percentage differences of column one.

As an example to provide further clarity, the silica oxide content (column two, row three) is 39.67% before normalisation whereas the silica content is 39.28% after normalisation (column three, row three).

It is also observed that rows one to five and rows seven to eleven show that the measured results of the oxides are lower compared to the theoretically determined oxide contents of columns two and three.

From these rows, the smallest error (1.49%) is noted for the content of Titanium oxide (TiO2) of column two, row ten. The theoretically determined value was found to be 1.57% whereas the experimentally determined value was found to be 0.92%. The difference between the contents is 0.65%.

The largest discrepancy is noted for the Sodium oxide (Na_2O) content of column two, row nine. An error of 1621.75% is noted. The content of sodium oxide theoretically determined is 1.72%. The experimentally determined quantity is 0.1% indicating a difference of 1.62%.

The Calcium and Silicon oxides are found to be in the greatest quantity compared to all the other oxides. The quantities measured experimentally are 42.22% and 32.08% respectively. The quantities determined theoretically were 22.08% and 44.81% respectively. The differences in quantities are noted to be 20.14% and 12.73%. The differences in percentages are much greater than those noted in the discussion of Titanium and Sodium oxide.

The percentage differences noted are 147.63% for the Calcium oxide and 39.67% for Silicon oxide. In both cases, the percentage differences are lower compared to the percentage difference of Sodium oxide (1621.75%).

Rows six as well as rows twelve to fifteen show that the oxide contents are overestimated upon comparing the measured results to the theoretically determined results. From these oxides, the oxide that yield the greatest error is that of Sulphur oxide (SO_3) of column two, row fourteen. The error recorded is 56.62%. The theoretical calculation yields a value of 1.79% whereas the measured value is found to be 0.78% indicating 1.01% difference.

Strontium oxide (SrO) of column two in row thirteen indicates a percentage difference of 18.75%. The theoretical value was noted to be 0.05% whereas the measured value was observed to be 0.06%. The difference between the two systems of measurement is a mere 0.01 percentage points.

There is no need to elaborate on the XRF results of columns four and five which neglect the loss on ignition value. These columns show the same trends discussed already for columns two and three.

4.5.2.2.4. Implications of the Findings between the Theoretical and Experimental XRF Results of Un-hydrated Mix

It was expected that the theoretical results on the materials in the dry state would be closely related to the measured results. The basis for this speculation is because the materials were assumed to be thoroughly homogenised during sampling for XRF analysis.

However, from the observations made in the preceding section, it would be appreciated that the speculation made does not hold true. That is to say, the large percentage differences show that the theoretically determined XRF results do not closely match the measured XRF results.

This finding suggests one of two things: (a) either the composite mix of A2-15 that was sent for XRF analysis was not homogenised properly, or (b) the sampling procedure described in Section 3.5 of Chapter three did not accurately reflect the different proportions of the composite mix.

To explain further, the measured oxides would depend on the distribution of the different phases (sand, water, cement, fly ash) in the sample selected for XRF analysis. If there is more of one material in the composite mix analysed for XRF, the consequence would be that the measured XRF analysis will not match the theoretically determined oxides which assumes that the mix is thoroughly homogenised and that the sample analysed for XRF is representative of the different proportions of the composite mix.

The observations in the previous section also reveal another aspect dealing with using percentage differences as a means to compare the theoretically determined oxides to the measured oxides. Using percentage differences is not desirable and can lead to misinterpretation. To explain further, consider the Silicon and Sodium oxides that were determined theoretically and measured experimentally:

The amount of Silicon oxide determined theoretically was 44.81%. The quantity measured experimentally was 32.08%. The percentage difference was found to be 39.67%.

With regards to the Sodium oxide content, the measured results revealed a 0.1% content whilst the theoretically determined analysis revealed a content of 1.72%. The percentage difference was found to be 1621.75%.

Whilst the Silicon oxide content shows the smallest percentage difference from the three oxides selected to explain the results, the absolute difference between the theoretically determined value and the measure value is found to be large. The absolute difference is recorded to be 12.73% between the measured and theoretical values.

Similarly, whilst the percentage difference of the sodium oxide content appears to be extremely large, the absolute differences between the measured and theoretically determined results are only 1.62%.

It can be argued also that utilising XRF to determine oxide contents of a composite material is extremely challenging. This statement is motivated by the varying percentage differences observed in the previous section.

Using the XRF results in this study is likely to lead to misinterpretation of the chemical make-up of a composite mix since the sampling procedure adopted does not fully account for the different phases accurately in their respective proportions.

The main implication of this study is that since the XRF results obtained between the measured and theoretically determined oxides do not match well, there would also be incongruity for the XRF results on the hydrated specimens. This will make it difficult to determine whether XRF is a useful technique for inferring hydration and whether the technique can be used to predict different blends of composite materials.

4.5.2.3. Part three: Comparison between XRF Results before and After Hydration

The results from conducting an XRF analysis after allowing for twenty eight days of curing showed varying percentage differences compared to the XRF analysis of the composite mix before the onset of hydration.

The above finding was expected. The final statement in the previous section speculated this outcome. One of the main reasons for the finding is due to the fact that the material selected for XRF analysis was in-homogenous and did not correctly reflect the proportions of the different phases in the material.

Five tables are presented for the comparison between the un-hydrated sample and the hydrated sample. The first table does not account for normalising the results. The second table normalises the results. The third table excludes the loss on ignition without normalising the results. The fourth table normalises the XRF results ignoring the loss on ignition value.

The reason for presenting five tables is to show that no matter what the technique used to compare the results, the findings are always the same.

4.5.2.3.1. Comparison using Actual Results

Table 4.5.2.6.1—1 shows the actual XRF results after twenty eight days of hydration along with the percentage differences computed theoretically and experimentally.

	1	2	3	4
1	OXIDE (%)	A	B	C
2	SiO_2	40.46	-9.71	26.11
3	Al_2O_3	13.59	-13.14	-5.70
4	Fe_2O_3	7.39	-6.41	131.76
5	CaO	22.72	2.88	-46.20
6	MgO	2.81	-4.43	90.00
7	K_2O	0.66	-6.02	107.19
8	Na_2O	1.77	2.74	1669.00
9	TiO_2	0.80	-13.90	-12.61
10	Mn_2O_3	0.14	-2.78	16.67
11	P_2O_5	0.20	5.63	-14.35
12	SrO	0.04	-22.05	-36.67
13	SO_3	0.87	11.40	-51.68
14	LOI	9.37	351.84	239.49
15	SUM	100.81		
16	A: XRF RESULTS AFTER 28 DAYS OF HYDRATION			
17	B: PERCENTAGE DIFFERENCES RELATIVE TO DAY 0 THEORETICAL RESULTS			
18	C: PERCENTAGE DIFFERENCES RELATIVE TO DAY 0 EXPERIMENTAL RESULTS			

Table 4.5.2.3.1-1: XRF Results for mix A2 after 28 Days of Hydration

It is observed that percentage differences computed using the theoretical results at day zero seem to be lower compared to the measured results.

The Aluminium oxide content (Al_2O_3) and Titanium oxide content (TiO_2) before hydration were the only two oxides that appeared to show close values compared to the measured XRF results after twenty eight days of hydration (rows three and nine).

The values reported indicate that Aluminium oxide yields a percentage difference of 13.14% for the theoretical results (column three) and 5.7% for the measured results (column four). With regards to the Titanium oxide content, the theoretical results differ by 13.9% whereas the measured results showed a difference of 12.61%.

The percentage differences of the XRF analysis using the theoretically determined results demonstrations that after twenty eight days of hydration, the oxide contents of Calcium, Sodium, Pentium and sulphur oxide has increased. The values reported are 2.88%, 2.74%, 5.63% and 11.40%.

However, the measured results shows that Calcium, Pentium and Sulphur oxide actually decreased by 46.20%, 14.35% and 51.68%. The Sodium oxide content shows that there is an increase of 1669.00%.

Some of the largest discrepancies noted between the measured twenty eight day results and the theoretically computed results are noted with Sulphur oxide. It is noted that there is an increase of 11.4%. Titanium oxide shows a decrease of 13.9%. Similarly, Aluminium and Silicon oxides indicate that over the course of twenty eight days of hydration, 13.14% and 9.17% had depleted.

Some of the largest differences noted with the measured results are with Sodium oxide which shows an astonishing increase of 1669%, the iron oxide content is found to have also increased significantly as 131.76% had been noted. Also, Potassium oxide showed a large discrepancy where a 107.19% increase was determined.

Some oxides of the results seemed to have matched the XRF twenty eight day results more closely than others. For the theoretical comparison, the oxides noted are with Sodium (2.74% lower), Manganese (2.78% lower) and Calcium oxide (2.88% greater). For the experimental comparison the oxides which were closely related were with Aluminium (5.70% lower), Titanium (12.6% lower) and Silicicon (26.11% greater) oxide.

With regards to the main oxides from the study of Sisomphon (2009), it was expected that Calcium and Sulphur oxide would show an increase in content whereas Silicon and Aluminium oxide would show a decrease in content.

These expectations cannot be confirmed based on either the experimental results or the theoretical results. The discrepancies in percentage difference using the theoretical and experimental results are outlined below:

The Calcium oxide content after twenty eight days of hydration compared to the theoretical results show an increase in content of 2.88% (column three, row five) whereas the results show a decrease of 46.20% (column four, row five) after comparing using the experimental results.

Similarly, the Sulphur oxide content using the theoretical results show an increase of 11.40% (column three, row thirteen) but a 51.68% (column four, row thirteen) decrease using the experimental results.

The Aluminium oxide content in both cases shows a depletion. However, the percentage differences are dissimilar. The difference compared to the theoretical results is 13.14% (column three, row three) whereas 5.7% is noted using the experimental results (column four, row three) for comparison.

The final oxide, namely Silicon oxide shows a depletion of 9.71% when compared to the theoretical results (column three, row two) but, when using the experimental results (column four, row two), an increase of 26.11% is noted.

It is also interesting to note the observations of the loss on ignition. The loss on ignition values reported show a significant development between the samples analysed using XRF before and after hydration.

The percentage differences of the loss on ignition values compared to the theoretical loss on ignition are reported to be 351.84% whereas the experimentally determined results when used as the basis for comparison yield a percentage difference of 239.49%. In both cases, the percentage differences show that the loss on ignition had increased significantly.

Before any implications can be drawn, the next section reviews the outcomes of the percentage differences using normalised results instead.

4.5.2.3.2. Comparison using Normalised Results

There is be no significant difference between comparing the actual oxides as was done in the previous section and in comparing the oxide contents after normalising the grand totals to sum up to 100% (column two, row fifteen). This was also observed when discussing the XRF analysis of the samples prior to hydration (see discussion for results of Table 4.5.2.1—1). Table 4.5.2.6.2—1 is presented to confirm the claim.

	1	2	3	4
1	OXIDE (%)	A	B	C
2	SiO_2	40.13	-10.47	24.69
3	Al_2O_3	13.48	-13.87	-6.76
4	Fe_2O_3	7.33	-7.20	129.16
5	CaO	22.53	2.02	-46.80
6	MgO	2.79	-5.23	87.87
7	K_2O	0.66	-6.82	104.87
8	Na_2O	1.75	1.88	1649.17
9	TiO_2	0.80	-14.62	-13.59
10	Mn_2O_3	0.14	-3.60	15.36
11	P_2O_5	0.20	4.74	-15.31
12	SrO	0.04	-22.71	-37.38
13	SO_3	0.86	10.46	-52.22
14	LOI at 950°C	9.29	348.03	235.69
15	SUM	100.00		
16	A: XRF AFTER 28 DAYS NORMALISED TO 100%			
17	B: PERCENTAGE DIFFERENCE RELATIVE TO DAY 0 NORMALISED THEORETICAL RESULTS			
18	C: PERCENTAGE DIFFERENCE RELATIVE TO DAY 0 NORMALISED EXPERIMENTAL RESULTS			

Table 4.5.2.3.2-1: Normalised XRF Results for mix A2 after 28 Days of Hydration

The normalising operation resulted in minor variation of the percentage differences reported in the previous section. To motivate the argument, a few percentage differences have been discussed and related to the percentage differences reported in the previous section.

The percentage differences of the oxides of Calcium, Sodium, Pentium and Sulphur were reported to be 2.88, 2.74, 5.63 and 11.40% after using the theoretical XRF results for comparison. The percentage differences of the same oxides after the normalising operation resulted in 2.02, 4.74 and 10.46% differences. It would be reasonable to assume that the previous percentage differences computed compared to these percentage differences are not significantly different. The main reason for the similarity could be attributed to the fact that the total sum of oxides before the normalising operation was nearly 100%. The actual value was recorded to be 100.81% (row , column of Table 4.2.3.1).

After having presented the XRF results for mix A2-15 before and after hydration and comparing the results using different techniques, it is appropriate to draw on the implication of the findings. This is done in the next section.

4.5.2.3.3. What can be concluded from the Comparison Using the Actual and Normalised Results?

After reflecting upon all the percentage differences, it is evident that the results had shown considerable variance. This made it difficult to establish whether the XRF results before and after hydration could be used to predict the degree and extent of hydration.

Some oxides showed an increase in content whilst other oxides showed a decrease in content.

With regards to the large loss on ignition value recorded, a new question arose. The question was whether the loss on ignition contents affected the XRF results that were presented?

It was not clear whether it would have been possible to infer the usefulness of using XRF analysis to assess the hydration rate and the degree of hydration if the loss on ignition results were excluded. Therefore, it was then decided that it would be necessary to exclude the loss on ignition values from the XRF analysis and recalculate the oxide contents in order to ascertain the effect of neglecting the loss on ignition value. The next section details the outcome of neglecting the loss on ignition before and after twenty eight days of hydration but and also shows the results when the loss on ignition was not neglected.

4.5.2.3.4. Comparison of XRF Results before and After Hydration using the Theoretical Results

	1	2	3	4	5	6
1	OXIDE (%)	A	B	C	D	E
2	SiO_2	45.77	40.13	44.24	12.33	3.35
3	Al_2O_3	15.98	13.48	14.86	15.66	7.01
4	Fe_2O_3	8.07	7.33	8.09	9.12	-0.19
5	CaO	22.56	22.53	24.84	0.10	-10.14
6	MgO	3.01	2.79	3.08	7.20	-2.31
7	K_2O	0.72	0.66	0.73	8.75	-0.60
8	Na_2O	1.76	1.75	1.93	0.23	-9.99
9	TiO_2	0.95	0.80	0.88	16.39	7.82
10	Mn_2O_3	0.15	0.14	0.15	5.60	-4.08
11	P_2O_5	0.19	0.20	0.22	-2.57	-13.08
12	SrO	0.05	0.04	0.04	24.31	16.56
13	SO_3	0.79	0.86	0.95	-8.17	-19.25
14	LOI at 950°C		9.29			
15	SiO_2	100.00	100.00	100.00	0.00	0.00
16	A: THEORETICAL XRF PRIOR TO HYDRATION, EXCLUDES LOSS ON IGNITION, NORMALISED TO 100%					
17	B: THEORETICAL XRF RESULTS AFTER 28 DAYS, ACCOUNTS FOR LOSS ON IGNITION, RESULTS NORMALISED TO 100%					
18	C: THEORETICAL XRF AFTER 28 DAYS, EXCLUDING LOI, NORMALISED TO 100%					
19	D: $\frac{(A-B)}{A} \times 100\%$					

20	E: $\frac{(A-C)}{A} \times 100\%$

Table 4.5.2.3.4-1: Comparison of Theoretical XRF Results for mix A2 Before and After Hydration

Columns D and E are formulated to enable a comparison the results shown in Columns A, B and C. Column D is expressed to represent the percentage differences of the XRF results after hydration which account for the loss on ignition value compared to the XRF results prior to hydration. Column E is formulated in a similar fashion to column D, except that the results used are those that excluded the loss on ignition value.

On the whole, the percentage differences show fewer discrepancies in column D than in column E. All the oxides (excepting four oxides) had, in column E, showed less error compared to the percentage differences given in column D.

Nonetheless, the percentage differences in Table 4.5.2.3.4—1 still show large discrepancies compared to the comparison of the XRF analysis in the previous two sections where the loss on ignition values were included.

Some of the results have been presented to motivate the observation. The percentage differences of the results when using the theoretically determined values had previously revealed that the oxides of Calcium, Sodium, Pentium and Sulphur had resulted in an increase of 2.02%, 1.88%, 4.74% and 10.46% (refer to Table 4.5.2.3—1). For the same oxides, the percentage differences after excluding the loss on ignition (Table 4.5.2.4—1) are noted to be 10.14%, 9.99%, 13.08% and 19.25%. It is clear that excluding the loss on ignition appears to still indicate variable results since the percentage differences are found to be large compared to the analysis where the loss on ignition value was not omitted. The next section details similar findings when the experimental results were used instead.

4.5.2.3.5. Comparison of XRF Results before and After Hydration using the Experimental Results

Thus far, a comparison of the theoretically calculated oxides compared to the measured oxide contents after twenty eight days has been presented. Similar observations had been detected for the oxide contents of the measured before and after hydration and have been documented in Table 4.5.2.3.5—1.

	1	2	3	4	5	6

	OXIDE (%)	A	B	C	D	E
1	SiO_2	44.24	32.18	33.10	27.26	25.19
2	Al_2O_3	14.86	14.46	14.87	2.72	-0.05
3	Fe_2O_3	8.09	3.20	3.29	60.42	59.29
4	CaO	24.84	42.36	43.56	-70.50	-75.35
5	MgO	3.08	1.48	1.53	51.72	50.34
6	K_2O	0.73	0.32	0.33	55.72	54.46
7	Na_2O	1.93	0.10	0.10	94.81	94.67
8	TiO_2	0.88	0.92	0.95	-4.97	-7.96
9	Mn_2O_3	0.15	0.12	0.12	21.37	19.13
10	P_2O_5	0.22	0.23	0.24	-7.10	-10.15
11	SrO	0.04	0.06	0.06	-44.84	-48.97
12	SO_3	0.95	1.80	1.85	-89.83	-95.24
13	LOI		2.77			
14	SUM	100.00	100.00	100.00		
15	A: XRF RESULTS AFTER 28 DAYS, EXCLUDES LOSS ON IGNITION, NORMALISED TO 100%					
16	B: EXPERIMENTAL XRF RESULTS, INCLUDES LOSS ON IGNITION, NORMALISED TO 100%					
17	C: EXPERIMENTAL XRF RESULTS, EXCLUDES LOSS ON IGNITION, NORMALISED TO 100%					
18	D: $\frac{(A-B)}{A} \times 100\%$					
19	E: $\frac{(A-C)}{A} \times 100\%$					

Table 4.5.2.3.5-1: Comparison of Experimental XRF Results for mix A2 Before and After Hydration

After neglecting the loss on ignition value from the analysis, the results appeared to show that the oxide contents before and after hydration did not change significantly.

In column C, excepting for five of the thirteen oxides, the percentage difference in oxide contents support the speculation followed from the theoretical observations in that the oxide contents do not vary between and after hydration since the percentage differences appeared to show less error compared to values in column B which accounted for the loss on ignition in the results.

The five oxides were for Calcium, Titanium, Pentium, Strontium and Sulphur and yielded percentage difference values of 75.53, 7.96, 10.15, 48.97 and 95.24% in column D and 70.5, 4.97, 7.10, 44.84 and 89.83% for column E. The differences could be regarded to be insignificant due to the varying oxides due to sampling errors.

4.5.2.4. Part Four: Implication of the Findings

From all that has been presented, observed and discussed, it would be reasonable to conclude the XRF analysis with stating that:

(a) The variable results would be mainly due to the variable nature of the material analysed for XRF. The sampling procedure could not guarantee that exact proportions of the material would have been collected.

(b) The oxide contents before and after hydration were similar after accounting for the effects of loss on ignition. Thus, the findings of Sisomphon (2009) who had shown changes in oxide contents are possibly because of the fact that Sisomphon had not accounted for the effects of loss on ignition.

(c) The loss on ignition value applied to samples at different periods could be used instead of XRF analysis to follow the course of hydration. However, special precaution would be warranted for the sampling a composite material for a loss on ignition analysis. If the sampling does not represent all the materials that contribute toward to composite and if incorrect proportions are sampled, the loss on ignition value would be questionable.

(d) In conclusion, the oxides of a material should not change. XRF analysis cannot distinguish changes between the mineral state of a material such as cement before and after hydration. XRF is only meant to determine the elemental oxides of a material. “What you put in should be what you get out”

5. Chapter 5: Conclusion

1. The inter-laboratory study demonstrated the importance of the operator, calibration and precision of testing equipment as well as the importance of using viable products such as reagents in the test procedures. The study also revealed that long term effects, such as pre-hydration due to improper storage and the natural ageing of cement with the loss on ignition test, can also affect the outcome of test results.
2. In terms of the chemical factors determined namely sulphate content, chloride content and insoluble residue content, the South African cements show good performance.
3. It was found that the sulphate contents of the German cement were higher than the Pakistani cement. It was also found that the local cements yielded lower sulphate contents compared to the German and Pakistani plain Portland cement. The lower sulphate contents were speculated to be due to the dilution effect that results from the incorporation of extenders into clinker.
4. The insoluble residue contents were difficult to determine compared to all the other chemical tests. The German and Pakistani cement had almost the same insoluble residue contents. It was also established that cement containing fly ash would have large insoluble residue contents and depending on how much fly ash is contained, the insoluble residue content would vary. Limestone containing cements would have low insoluble residue content as well as blast furnace containing cements. These cements would probably always be found to have insoluble residue contents that would satisfy the requirements of EN 196-2 (2005).
5. In terms of strength development, the German cement showed far superior early strength characteristics.
6. The Pakistani class 42.5 ordinary Portland cement satisfied all the requirements stipulated by SANS 197. Furthermore, the performance of the Pakistani cement appears to be similar to the South African cements of the class 42.5 group except for setting times which were observed to be quicker.
7. Comparing cements of different composition and type should be done on a contextual basis. “R” cements may be formulated for specific purposes as with “N” cements. Thus, whilst the properties of one cement may be appropriate for a certain application, it might also be inappropriate for other types of applications.

8. The setting times of the Pakistani and German cement were found to be the shortest. South African cements have much longer setting times. It could be argued that it might be more beneficial to use a cement having a long setting time in hot weather to counter the effects of accelerated setting. In this case, the Pakistani and German cements would be unsuitable compared to the local cements (excepting cement G which set very fast) which have fairly extensive setting times compared to these imported cements.

9. The Pakistani cement showed excellent workability which could be attributed to the coarse nature of the cement as was found from the specific surface area results. This cement showed superior performance in terms of workability even after comparing to some of the class 32.5 cements which had an abundance of fly ash and were expected to show the most superior performance.

10. The results of the hydration study involving strength and durability revealed contradicting results. However, on the whole, from a general point of view from the twenty eight day results, it appeared that continuous moist curing in water yielded better performance and based on this general trend, the importance of continuous moist curing in water is realised. Curing in air resulted (in general after twenty eight days) in inferior strength and durability whereas the specimens cured in the solar chamber were found to have better strengths than specimens cured in air but not as good strengths as the specimens cured in water.

11. The Pycnometer apparatus appears to be a useful technique to infer the degree and rate of hydration as a trend was noticeable and distinguishable between the readings found between the three different classes of cements in the control, 15% and 30% fly ash mixes. However, further work is required on improving the process of sample preparation so that the effects of inhomogeneity can be eliminated.

12. From the x-ray fluorescence study, the oxides of a material should not change. XRF analysis cannot distinguish changes between the mineral state of a material such as cement before and after hydration. XRF is only meant to determine the elemental oxides of a material. “What you put in should be what you get out.”

13. It could be argued that XRF analysis depends greatly upon the method of sampling. This aspect was not investigated but is hypothesised. The argument can however, be accentuated with a simple argument: Suppose that a sample of a composite material was to be studied. If the sample had not been properly homogenised and contained more of

one type of material than the other materials which make up the composite, the XRF results would naturally not be representative of the proportions of the material which make up the composite.

14. Furthermore, it was found the oxide contents do not vary before and after hydration. The results of Sisomphon (2009) had not accounted for the effects of the loss on ignition values after the different periods of hydration. If the results had accounted for the loss on ignition, it would have been found that the oxide contents would not have actually varied much at all between the different periods of curing.

15. It would be safe to conclude that the XRF analysis would not be sensible as a tool for following and inferring the rate and degree of hydration over time. However, the loss on ignition values would give a better indication.

6. Recommendations for Future Work

6.1. Chemical Tests

The items selected for chemical investigation were limited to insoluble residue, sulphate and chloride content. Other chemical properties such as the magnesia, silica, manganese and alkali content could be explored.

6.2. Physical Tests

The range of physical tests on the cements can be extended beyond strength tests to include heat of hydration, soundness or other tests depending on interest.

6.3. Solar Chamber Studies

Durability aspects that were investigated were limited to sorptivity studies. The strength tests were limited to one month only.

For a better appreciation and understanding of the influence of the solar chamber, the period of investigation should be extended as well as the range of durability tests. The periods should extend over different seasons of the year and include comparison with other curing regimes.

The cementitious materials could be extended to include other types of cements such as masonry cements as well as by-products from other industries.

The range of mixes can be extended to include mixes lean in cement to rich in cement quantity and different aggregates.

The solution in the solar chamber could be made to be laden with ions such as chlorides and sulphates and the performance compared to standard tests methods dealing with chloride and sulphate attack. The performance of the solar chamber with no water could also be of interest if the only interest is the influence of fluctuating temperatures in a contained environment.

Techniques to improve the performance of the solar chamber such as through lining the solar chamber with different materials, especially insulating materials would be interesting to investigate.

Jardine (1976) made use of salts to vary the humidity in a humidity chamber: $NaBr2H_2O$ produced a 58%RH sodium bromide and sodium iodide produced a 39% RH. A study on the influence of salts to give a constant humidity but fluctuating temps could be of interest.

Concrete in aquariums and concrete in the shopping areas where there are a great deal of flowers might be of interest as plants give off CO_2 in the absence of light. Whilst this proposal may seem peculiar, it could be of interest in the field of accelerated carbonation studies, especially on thin specimens such as tiles. Further motivation for this could be the fact that there is great interest in environmental factors influencing concrete as well as great conscience for preserving the environment. So why not place concrete in a solar chamber with a flower bed of flowers?

The performance of composite could be interesting. Materials having different thermal insulating properties could be of special interest in an environment of fluctuating temperature in the solar chamber. Examples could be concrete containing aluminium or bamboo possibly?

6.4. Cementitious Materials in Industry

Fly ash and slag are by far the most common cementitious materials used in the cement industry. Silica fume on the other hand appears to be uncommon. In fact, from the catalogues of the four main cement manufacturers, it appears that silica fume is not being used at all.

It is unclear as to the reason for the lack of popularity. However, speculating suggests that the reason for the silica being uncommon may be due to the relatively small quantities available.

Further investigation into the potential application of silica fume in industry may be beneficial from an economic as well as a materials point of view. Silica fume is a by-product from the silicon industry and so, could potentially offset cost and furthermore, promotes certain properties such as strength development and improved durability. Finally, between just 3 to 15% of silica fume can have marked influence on the properties of concrete.

For a better understanding and appreciation of the performance of cementitious materials in industry, cements from third party manufacturers should be investigated.

6.5. Pycnometer Studies

The range of materials, curing regimes, mixes as well as the extent of the period of the study can be extended.

Perhaps the water (or any other solution of interest such as a sulphated solution for example) absorption of reinforced concrete sections, or mixes containing trace elements can be used to infer the performance of such mixes.

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Appendix 1.1: XRF Results of Cements

32.5 Cements														
code	Fe2O3	Al2O3	SiO2	CaO	MgO	K2O	Na2O	TiO2	Mn2O3	P2O5	SrO	SO3	LOI at 950	SUM
A1	3.25	15.69	34.94	39.08	1.71	0.37	0.11	0.98	0.14	0.21	0.06	1.71	1.17	96.17
A2	3.19	14.41	32.08	42.22	1.48	0.32	0.10	0.92	0.12	0.23	0.06	1.79	2.76	96.49
B	2.76	12.60	32.31	42.27	3.92	0.79	0.19	1.04	0.26	0.19	0.08	2.18	0.77	96.60
C	1.54	9.42	31.22	45.50	6.98	0.89	0.24	0.84	0.43	0.03	0.07	2.26	0.00	97.88
42.5 Cements														
D1	3.11	8.37	23.91	55.96	1.73	0.20	0.08	0.68	0.16	0.15	0.04	2.18	3.12	96.58
D2	2.69	7.84	24.70	54.90	1.54	0.47	0.09	0.56	0.10	0.12	0.04	2.76	3.72	96.84
E	2.88	9.62	27.21	50.44	3.32	0.76	0.21	0.82	0.16	0.16	0.06	2.76	1.45	96.97
F1	3.42	5.37	20.32	62.37	2.36	0.71	0.24	0.34	0.10	0.10	0.16	2.83	1.63	96.53
F2	2.36	4.50	19.79	62.91	1.96	0.91	0.20	0.24	0.04	0.25	0.30	3.27	2.83	97.20
G	2.49	3.87	17.44	60.47	2.41	0.56	0.18	0.38	0.06	0.06	0.02	2.30	9.58	97.33
52.5 Cements														
H1	3.43	4.99	21.25	61.69	2.88	0.24	0.09	0.39	0.50	0.08	0.03	2.76	1.69	96.59
H2	2.66	4.31	20.24	63.34	1.61	0.46	0.07	0.40	0.11	0.07	0.02	2.89	3.53	97.05
I	3.19	6.56	21.60	60.39	1.73	0.16	0.09	0.63	0.17	0.15	0.04	2.87	2.27	96.66

Actual Measured XRF Results of Cements in Study

32.5 Cements															
CODE	Fe2O3	Al2O3	SiO2	CaO	SO3	MgO	K2O	Na2O	TiO2	Mn2O3	P2O5	SrO	LOI at 950	SUM	
A1	3.38	16.31	36.33	40.64	1.78	1.78	0.38	0.11	1.02	0.15	0.22	0.06	1.22	100.00	
A2	3.31	14.93	33.25	43.76	1.86	1.53	0.33	0.10	0.95	0.12	0.24	0.06	2.86	100.00	
B	2.86	13.04	33.45	43.76	2.26	4.06	0.82	0.20	1.08	0.27	0.20	0.08	0.80	100.00	
C	1.57	9.62	31.90	46.49	2.31	7.13	0.91	0.25	0.86	0.44	0.03	0.07	0.00	100.00	
32.5 AVG	2.78	13.48	33.73	43.66	2.05	3.63	0.61	0.16	0.98	0.24	0.17	0.07	1.22	100.00	
42.5 Cements															
D1	3.22	8.67	24.76	57.94	2.26	1.79	0.21	0.08	0.70	0.17	0.16	0.04	3.23	100.00	
D2	2.78	8.10	25.51	56.69	2.85	1.59	0.49	0.09	0.58	0.10	0.12	0.04	3.84	100.00	
E	2.97	9.92	28.06	52.02	2.85	3.42	0.78	0.22	0.85	0.16	0.16	0.06	1.50	100.00	
F1	3.54	5.56	21.05	64.61	2.93	2.44	0.74	0.25	0.35	0.10	0.10	0.17	1.69	100.00	
F2	2.43	4.63	20.36	64.72	3.36	2.02	0.94	0.21	0.25	0.04	0.26	0.31	2.91	100.00	
G	2.56	3.98	17.92	62.13	2.36	2.48	0.58	0.18	0.39	0.06	0.06	0.02	9.84	100.00	
42.5 AVG	2.87	6.02	21.84	60.87	2.88	2.59	0.76	0.21	0.46	0.09	0.15	0.14	3.99	100.00	
52.5 Cements															
H1	3.55	5.17	22.00	63.87	2.86	2.98	0.25	0.09	0.40	0.52	0.08	0.03	1.75	100.00	
H2	2.74	4.44	20.86	65.27	2.98	1.66	0.47	0.07	0.41	0.11	0.07	0.02	3.64	100.00	
I	3.30	6.79	22.35	62.48	2.97	1.79	0.17	0.09	0.65	0.18	0.16	0.04	2.35	100.00	
52.5 AVG	3.12	5.60	21.76	63.12	2.92	2.25	0.41	0.12	0.48	0.22	0.11	0.06	2.93	100.00	

Normalised XRF Results of Cements in Study to Ensure Grand Totals Equate to 100 Percent

Explanation of procedure for normalising XRF results:

Consider cement A1. The total of the oxides summated to 96.17%. In order to normalise the results to 100%, it is necessary to take each individual oxide and to then divide the percentage of those individual oxides by the total of 96.17%.

For instance, the Iron oxide content was measured to be 3.25%. Using this value and dividing by 96.17% results in 3.38% which is what is shown in Figure A1.2 for the Iron oxide content of cement A1.

The procedure explained above is repeated for each oxide so that when the totals are calculated, it sums to 100%.

Appendix 2.1: Sulphate Test Results

Cement B	Sample 1		Sample 2	
Crucible Identity	43.0000		no87	
Mass of Sample (A)	1.0005	g	1.0003	g
Mass of Crucible (B)	17.7040	g	17.0307	g
Mass of Crucible+$BaSO_4$	17.7473	g	17.0724	g
Mass of $BaSO_4$	0.0433		0.0417	
SO3%=D/A*34.3	1.4844		1.4299	
Difference Between Sample 1 and 2	0.0546			
Accept/Reject (Difference<0.14%)	Accept			
AVG SO_3%	1.4572			

Sulphate Test Results of Cement B

Cement C	Sample 1		Sample 2	
Crucible Identity	43.0000		45.0000	
Mass of Sample (A)	1.0001	g	0.9998	g
Mass of Crucible (B)	17.6907	g	17.9520	g
Mass of Crucible+BaSO	17.7179	g	17.9829	g
Mass of $BaSO_4$	0.0272		0.0309	
SO3%=D/A*34.3	0.9329		1.0601	
Difference Between Sample 1 and 2	0.1272			
Accept/Reject (Difference<0.14%)	Accept			
AVG SO_3%	0.9965			

Sulphate Test Results of Cement C

Cement F1	Sample 1		Sample 2	
Crucible Identity	55.0000		no87	
Mass of Sample (A)	0.9998	g	1.0001	g
Mass of Crucible (B)	17.2881	g	17.9711	g
Mass of Crucible+$BaSO_4$ (C)	17.3637	g	18.0459	g
Mass of $BaSO_4$ = D = C-B	0.0756		0.0748	
SO3%=D/A*34.3	2.5936		2.5654	
Difference Between Sample 1 and 2	0.0282			
Accept/Reject (Difference<0.14%)	Accept			
AVG SO_3%	2.5795			

Sulphate Test Results of Cement F1

Cement F2	Sample 1		Sample 1	
Crucible Identity	47.0000		51.0000	
Mass of Sample (A)	1.0001	g	0.9999	g
Mass of Crucible (B)	17.2205	g	17.3737	g
Mass of Crucible+$BaSO_4$ (C)	17.3030	g	17.4601	g
Mass of $BaSO_4$ = D = C-B	0.0825		0.0864	
SO3%=D/A*34.3	2.8295		2.9638	
Difference Between Sample 1 and 2	0.1343			
Accept/Reject (Difference<0.14%)	Accept			
AVG SO_3%	2.8966			

Sulphate Test Results of Cement F1

Cement G	Sample 1		Sample 2	
Crucible Identity	69.0000		no83	
Mass of Sample (A)	1.0005	g	1.0002	g
Mass of Crucible (B)	16.2395	g	18.1299	g
Mass of Crucible+$BaSO_4$ (C)	16.3040	g	18.1979	g
Mass of $BaSO_4$ = D = C-B	0.0645		0.0680	
SO3%=D/A*34.3	2.2112		2.3319	
Difference Between Sample 1 and 2	0.1207			
Accept/Reject (Difference<0.14%)	Accept			
AVG SO_3%	2.2716			

Sulphate Test Results of Cement G

Appendix 2.2: Insoluble Residue Test Results

| | | |

Insoluble Residue - Cement C				
First Attempt				
Crucible id	69		67	
Mass of crucible (M1)	18.1172	g	17.3287	g
Mass of Sample (M2)	1.0001	g	0.9998	g
Mass of crucible + residue (M3)	18.121	g	17.3359	g
Mass of residue (M3-M1) = (M4)	0.0038	g	0.0072	g
Insoluble residue (M4/M2)*100	0.379962	%	0.720144	%
Difference		-0.34018		
Accept/Reject (0.08%)	Reject			
Average insoluble residue	0.550053			
Second Attempt				
Crucible id	67		cl744	
Mass of crucible (M1)	17.3168	g	17.7445	g
Mass of Sample (M2)	1.0001	g	1	g
Mass of crucible + residue (M3)	17.3575	g	17.782	g
Mass of residue (M3-M1) = (M4)	0.0407	g	0.0375	g
Insoluble residue (M4/M2)*100	4.069593	%	3.75	%
Difference		0.319593		
Accept/Reject (0.08%)	Reject			
Average insoluble residue	3.909797			

Insoluble Residue Test Results of Cement C

Insoluble Residue - Cement F1				
First Attempt				
Crucible id	68		56	
Mass of crucible (M1)	18.3629	g	17.9973	g
Mass of Sample (M2)	0.9995	g	1.0005	g
Mass of crucible + residue (M3)	18.3774	g	18.0077	g
Mass of residue (M3-M1) = (M4)	0.0145	g	0.0104	g
Insoluble residue (M4/M2)*100	1.450725	%	1.03948	%
Difference		0.411245		
Accept/Reject (0.08%)	Reject			
Average insoluble residue	1.245103			
Second Attempt				
Crucible id	42		52	
Mass of crucible (M1)	17.8436	g	18.029	g
Mass of Sample (M2)	0.9998	g	1.0001	g
Mass of crucible + residue (M3)	17.8491	g	18.0338	g
Mass of residue (M3-M1) = (M4)	0.0055	g	0.0048	g
Insoluble residue (M4/M2)*100	0.55011	%	0.479952	%
Difference		0.070158		
Accept/Reject (0.08%)	Accept			
Average insoluble residue	0.515031			

Insoluble Residue Test Results of Cement F1

Insoluble Residue- Cement F2										
First Attempt					Second Attempt					
Crucible id	43		25		Crucible id	86		63		
Mass of crucible (M1)	17.6938	g	17.9557	g	Mass of crucible (M1)	17.8889	g	17.0658	g	
Mass of Sample (M2)	1.0001	g	1.0003	g	Mass of Sample (M2)	0.9999	g	0.9997	g	
Mass of crucible + residue (M3)	17.6995	g	17.9603	g	Mass of crucible + residue (M3)	17.9198	g	17.0731	g	
Mass of residue (M3-M1) = (M4)	0.0057	g	0.0046	g	Mass of residue (M3-M1) = (M4)	0.0309	g	0.0073	g	
Insoluble residue (M4/M2)*100	0.569943	%	0.459862	%	Insoluble residue (M4/M2)*100	3.090309	%	0.730219	%	
Difference		0.110081			Difference		2.36009			
Accept/Reject (0.08%)	Reject				Accept/Reject (0.08%)	Reject				
Average insoluble residue	0.514903				Average insoluble residue	1.910264				
Third Attempt										
Crucible id	45		43							
Mass of crucible (M1)	17.534	g	17.6744	g						
Mass of Sample (M2)	0.9998	g	1.0001	g						
Mass of crucible + residue (M3)	17.5455	g	17.6859	g						
Mass of residue (M3-M1) = (M4)	0.0115	g	0.0115	g						
Insoluble residue (M4/M2)*100	1.15023	%	1.149885	%						
Difference		0.000345								
Accept/Reject (0.08%)	Accept									
Average insoluble residue	1.150058									

Insoluble Residue Test Results of Cement F2

Insoluble Residue- Cement G				
First Attempt				
Crucible id	57		58	
Mass of crucible (M1)	17.7962	g	17.87	g
Mass of Sample (M2)	1.0003	g	1	g
Mass of crucible + residue (M3)	17.8051	g	17.8813	g
Mass of residue (M3-M1) = (M4)	0.0089	g	0.0113	g
Insoluble residue (M4/M2)*100	0.889733	%	1.13	%
Difference		-0.24027		
Accept/Reject (0.08%)	Reject			
Average insoluble residue	1.009867			
Second Attempt				
Crucible id	51		42	
Mass of crucible (M1)	17.3614	g	17.8372	g
Mass of Sample (M2)	1.0001	g	0.9996	g
Mass of crucible + residue (M3)	17.3821	g	17.8549	g
Mass of residue (M3-M1) = (M4)	0.0207	g	0.0177	g
Insoluble residue (M4/M2)*100	2.069793	%	1.770708	%
Difference		0.299085		
Accept/Reject (0.08%)	Reject			
Average insoluble residue	1.920251			

Insoluble Residue Test Results of Cement G

Appendix 2.3: Chloride Test Results

Chloride Test Results							
Cement B		Sample 1		Sample 2		Blank	
Mass of Sample	M1	4.9997	g	5.0003	g		g
0.05 molar $AgNO_3$		5	ml	5	ml	5	ml
initial vol of NH4SCN	A	0	ml	0	ml	0	ml
Final vol of NH4SCN	B	4.5	ml	4.6	ml	4.1	ml
Titrated vol of NH4SCN(ml)	(B-A)	4.5	V1	4.6	V1	4.1	V2
%Cl=0.17773*(V2-V1)/M1		-0.01418		-0.01773			
Difference		0.003544					
Accept/Reject(0.01%)		Accept					
AVG % Cl		-0.01596	Therefore take as zero				
Cement C		Sample 1		Sample 2		Blank	
Mass of Sample	M1	5.0002	g	4.9997	g		g
0.05 molar $AgNO_3$		5	ml	5	ml	5	ml
initial vol of NH4SCN	A	0	ml	0	ml	0	ml
Final vol of NH4SCN	B	4.3	ml	4.2	ml	4.1	ml
Titrated vol of NH4SCN(ml)	(B-A)	4.3	V1	4.2	V1	4.1	V2
%Cl=0.17773*(V2-V1)/M1		-0.00709		-0.00355			
Difference		-0.00355					
Accept/Reject(0.01%)		Accept					
AVG % Cl		-0.00532	Therefore take as zero				
Cement F1		Sample 1		Sample 2		Blank	
Mass of Sample	M1	4.9998	g	5	g		g
0.05 molar $AgNO_3$		5	ml	5	ml	5	ml
initial vol of NH4SCN	A	0	ml	0	ml	0	ml
Final vol of NH4SCN	B	4.2	ml	4.2	ml	4.1	ml
Titrated vol of NH4SCN(ml)	(B-A)	4.2	V1	4.2	V1	4.1	V2
%Cl=0.17773*(V2-V1)/M1		-0.00355		-0.00355			
Difference		-1.4E-07					
Accept/Reject(0.01%)		Accept					
AVG % Cl		-0.00355	Therefore take as zero				
Cement F2		Sample 1		Sample 2		Blank	
Mass of Sample	M1	5.0005	g	5.0001	g		g
0.05 molar $AgNO_3$		5	ml	5	ml	5	ml
initial vol of NH4SCN	A	0	ml	0	ml	0	ml
Final vol of NH4SCN	B	1.8	ml	1.8	ml	4.1	ml
Titrated vol of NH4SCN(ml)	(B-A)	1.8	V1	1.8	V1	4.1	V2
%Cl=0.17773*(V2-V1)/M1		0.08155		0.081556			
Difference		-6.5E-06					
Accept/Reject(0.01%)		Accept					
AVG % Cl		0.081553					
Cement G		Sample 1		Sample 2		Blank	
Mass of Sample	M1	5.0003	g	4.9999	g		g
0.05 molar $AgNO_3$		5	ml	5	ml	5	ml
initial vol of NH4SCN	A	0	ml	0	ml	0	ml
Final vol of NH4SCN	B	4.2	ml	4.4	ml	4.1	ml
Titrated vol of NH4SCN(ml)	(B-A)	4.2	V1	4.4	V1	4.1	V2
%Cl=0.17773*(V2-V1)/M1		-0.00355		-0.01064			
Difference		0.007092					
Accept/Reject(0.01%)		Accept					
AVG % Cl		-0.00709	Therefore take as zero				

Chloride Test Results of Cements

Appendix 3.1: Cement Characteristic Strength Results

*2dav=two day average, 7dav=seven day average, 28dav=twenty eight day average

Class 32.5 Cement Characteristic Strengths (MPa)					
	2d1	2d2	2dav	mass (g)	temp (Deg Celsius)
A1	14.2	14.6	14.4	577.0	22.8
A2	16.7	16.9	16.8	576.2	22.8
B	10.6	10.6	10.6	573.2	23.0
C	7.6	7.8	7.7	581.4	23.0
	7d1	7d2	7dav	mass (g)	temp (Deg Celsius)
A1	23.2	23.3	23.3	578.3	22.8
A2	29.5	29.4	29.5	576.1	22.8
B	18.6	19.1	18.9	571.4	23.0
C	19.7	19.1	19.4	581.8	23.0
	28d1	28d2	28dav	mass (g)	temp (Deg Celsius)
A1	40.0	40.6	40.3	579.5	22.8
A2	47.6	47.2	47.4	574.3	22.8
B	39.9	39.5	39.7	571.2	23.0
C	45.0	44.3	44.7	581.7	23.0

Class 32.5 Cement Characteristic Strengths

Class 42.5 Cement Characteristic Strengths (MPa)					
	2d1	2d2	2dav	mass (g)	temp (Deg Celsius)
D1	23.9	24.5	24.2	576.1	22.8
D2	22.2	23.2	22.7	583.6	23.0
E	17.1	17.5	17.3	581.2	23.0
F1	22.6	22.7	22.7		23.0
BAM			37.3		
G	25.7	24.1	24.9	580.5	22.9
	7d1	7d2	7dav	mass (g)	temp (Deg Celsius)
D1	41.9	42.0	42.0	579.5	22.8
D2	38.8	38.8	38.8	584.0	23.0
E	29.4	28.7	29.1	582.2	23.0
F1	36.7	35.7	36.2	586.1	23.0
BAM			48.0		
G	40.1	39.8	40.0	574.1	22.9
	28d1	28d2	28dav	mass (g)	temp (Deg Celsius)
D1	57.9	58.4	58.2	579.0	22.8
D2	53.8	54.5	54.2	585.2	23.0
E	47.1	47.6	47.4	582.0	23.0
F1	49.0	49.7	49.4	585.9	23.0
BAM			56.8		
G	49.5	49.9	49.7	574.6	22.9

Class 42.5 Cement Characteristic Strengths

Class 52.5 Cement Characteristic Strengths (MPa)					
	2d1	2d2	2dav	mass (g)	temp (Deg Celsius)
H1	23.4	23.6	23.5	580.5	23.0
H2	29.0	29.2	29.1	587.3	23.0
I	29.4	29.6	29.5	572.5	22.8
	7d1	7d2	7dav	mass (g)	temp (Deg Celsius)
H1	44.9	44.5	44.7	581.4	23.0
H2	48.1	47.2	47.7	585.9	23.0
I	45.8	45.9	45.9	573.9	22.8
	28d1	28d2	28dav	mass (g)	temp (Deg Celsius)
H1	61.4	64.3	62.9	581.9	23.0
H2	62.5	58.0	60.3	584.6	23.0
I	57.8	57.2	57.5	574.0	22.8

Class 52.5 Cement Characteristic Strengths

Appendix 3.2: Cement Setting Time Results

Cement [C]	Type of Cement	Water demand %	Initial Set time	Final set time (time after initial set)
A1	CEM I/V B-V 32.5N	32.6	4hrs23mins	2hrs15mins
A2	CEM IV B-V 32.5R	28.6	4hrs36mins	0hrs48mins
B	CEM V/A (S-V) 32.5 N	30	4hrs21mins	0hrs59mins
C	CEM III A 32.5 N	30	4hrs07mins	0hrs44mins
D1	CEM II A-M (V-L) 42.5N	29	3hrs57mins	0hrs41mins
D2	CEM II A/M (V-L) 42.5R	28.9	4hrs05mins	1hrs03mins
E1	CEM I 42.5 N	26	2hrs36mins	0hrs30mins
E2	CEM I 42.5 N	29.6	2hrs25mins	0hrs45mins
F	CEM II B-M (S-V) 42.5N	29.8	3hrs34mins	0hrs50mins
G	CEM II A-L 42.5N	29.6	2hrs10mins	0hrs49mins
H1	CEMI 52.5N	31.6	3hrs43mins	00hrs42 mins
H2	CEM I 52.5R	31	3hrs34mins	0hrs46mins
I	CEM II A-V 52.5 N	30.6	4hrs32mins	0hrs52mins

Cement Setting Time Results

Appendix 3.3: Loss on Ignition Results

Cement B	Sample 1		Sample 2	
Crucible ID	42		55	
Mass of Crucible (A)	17.8475	g	17.2918	g
Mass of Sample (B)	1.0001	g	1.0005	g
Mass of Crucible and Residue ©	18.8403	g	18.2844	g
Weight Loss (D)= A + B - C	0.0073	g	0.0079	g
LOI% = 100*(D/B)	0.729927	%	0.789605	%
Difference	0.059678			
Accept/Reject: (Diff of Sample 1 & 2<0.08%)	Accept			
AVG LOI	0.759766	%		

Loss on Ignition Results for Cement B

Cement C	Sample 1		Sample 2	
Crucible ID	48		62	
Mass of Crucible (A)	17.587	g	17.0593	g
Mass of Sample (B)	0.9995	g	0.9999	g
Mass of Crucible and Residue .(C)	18.5891	g	18.062	g
Weight Loss (D)= A + B - C	-0.0026	g	-0.0028	g
LOI% = 100*(D/B)	-0.26013	%	-0.28003	%
Difference	0.019898			
Accept/Reject: (Diff of Sample 1 & 2<0.08%)	Accept			
AVG LOI	-0.27008	%	negative implies oxidation	

Loss on Ignition Results for Cement C

Cement F1	Sample 1		Sample 2	
Crucible ID	59.0000		69.0000	
Mass of Crucible (A)	17.9692	g	18.1159	g
Mass of Sample (B)	0.9999	g	0.9997	g
Mass of Crucible and Residue ©	18.9525	g	19.0984	g
Weight Loss (D)= A + B - C	0.0166	g	0.0172	g
LOI% = 100*(D/B)	1.6602	%	1.7205	%
Difference	0.0604			
Accept/Reject: (Diff of Sample 1 & 2<0.08%)	Accept			
AVG LOI	1.6903	%		

Loss on Ignition Results for Cement F1

Cement F2	Sample 1		Sample 2	
Crucible ID	58		69	
Mass of Crucible (A)	17.8741	g	18.1215	g
Mass of Sample (B)	0.9995	g	0.9996	g
Mass of Crucible and Residue ©	18.8436	g	19.091	g
Weight Loss (D)= A + B - C	0.03	g	0.0301	g
LOI% = 100*(D/B)	3.001501	%	3.011204	%
Difference	0.009704			
Accept/Reject: (Diff of Sample 1 & 2<0.08%)	Accept			
AVG LOI	3.006353	%		

Loss on Ignition Results for Cement F2

Cement G	Sample 1		Sample 2	
Crucible ID	47small		47 big	
Mass of Crucible (A)	17.8056	g	17.2249	g
Mass of Sample (B)	0.9996	g	0.9998	g
Mass of Crucible and Residue ©	18.7139	g	18.1330	g
Weight Loss (D)= A + B - C	0.0913	g	0.0917	g
LOI% = 100*(D/B)	9.1337	%	9.1718	%
Difference	0.0382			
Accept/Reject: (Diff of Sample 1 & 2<0.08%)	Accept			
AVG LOI	9.1527	%		

Loss on Ignition Results for Cement G

Appendix 4.1: Concrete Strength Results

Cement A1	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2603.7	276	27.6	23.6
2	2558.5	223.2	22.32	
3	2566.4	210.1	21.01	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2483.7	240	24	24.3
2	2475.6	257	25.7	
3	2364.6	232	23.2	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2439.4	296	29.6	30.3
2	2373.5	315	31.5	
3	2524	298	29.8	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2580	277	27.7	28.9
2	2493	305	30.5	
3	2612.6	285	28.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2315.1	297	29.7	30.1
2	2368.3	304	30.4	
3	2533.7	303	30.3	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2525.4	311	31.1	31.0
2	2444.4	309	30.9	
3	2529	310	31	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2584	407	40.7	40.1
2	2582	401	40.1	
3	2620.2	396	39.6	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2570.3	360	36	36.4
2	24446.4	350	35	
3	22584.6	383	38.3	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2492.4	409	40.9	41.0
2	2470.1	412	41.2	
3	2521	410	41	

Concrete Strength Results for Cement A1

Cement A2	4Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2459.1	230	23	24.1
2	2621.9	250	25	
3	2522.5	244	24.4	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2329.3	237	23.7	23.2
2	2358.3	230	23	
3	2377	230	23	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2385.8	277	27.7	27.6
2	2323.5	276	27.6	
3	2480.2	275	27.5	
	8Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2616.9	310	31	32.2
2	2647	330	33	
3	2539.8	325	32.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2598.5	325	32.5	32.7
2	2409	325	32.5	
3	2425	330	33	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2467.6	347	34.7	33.3
2	2487.5	322	32.2	
3	2512.5	330	33	
	29Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2546.3	426	42.6	41.7
2	2255.8	446	44.6	
3	2592.2	378	37.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2273.5	382	38.2	36.0
2	2412.4	335	33.5	
3	2320.2	362	36.2	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2569.1	435	43.5	42.9
2	2460	425	42.5	
3	2491.4	427	42.7	

Concrete Strength Results for Cement A2

Cement B	4Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2585.6	220	22	21.7
2	2632.4	225	22.5	
3	2510.6	205	20.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2536.1	195	19.5	21.1
2	2665.8	220	22	
3	2599.3	218	21.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2595.3	208	20.8	21.5
2	2491.4	215	21.5	
3	2547.3	221	22.1	
	8Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2669	263	26.3	26.0
2	2629.7	260	26	
3	2583	256	25.6	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2506.7	240	24	25.2
2	2526.1	255	25.5	
3	2432.4	260	26	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2526.4	326	32.6	31.1
2	2553.1	307	30.7	
3	2496.7	299	29.9	
	29Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2585.6	350	35	34.4
2	2606.5	337	33.7	
3				
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2430.6	297	29.7	30.2
2	2537.5	306	30.6	
3				
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2592.6	315	31.5	32.0
2	2549.3	332	33.2	
3	2481.6	312	31.2	

Concrete Strength Results for Cement B

Cement C	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2642.7	160	16	16.4
2	2434.2	165	16.5	
3	2605.1	168	16.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2354.7	180	18	18.4
2	2559.2	184	18.4	
3	2543.5	187	18.7	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2520.7	218	21.8	22.5
2	2554.4	220	22	
3	2558	236	23.6	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2602.1	268	26.8	26.7
2	2450.5	259	25.9	
3	2480	274	27.4	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2469.7	250	25	26.2
2	2543.5	273	27.3	
3	2514.4	263	26.3	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2551.3	270	27	28.8
2	2518.9	303	30.3	
3	2586	290	29	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2754	447	44.7	43.9
2	2569	437	43.7	
3	2577	434	43.4	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2554.3	380	38	37.0
2	2505.1	360	36	
3	2657.3	370	37	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2655			39.0
2	2523.5	380	38	
3	2565	400	40	

Concrete Strength Results for Cement C

Cement D1	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2436.3	430	43	41.7
2	2618.9	415	41.5	
3	2599.4	405	40.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2531.7	404	40.4	40.0
2	2524.2	400	40	
3	2618.7	395	39.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2450.1	365	36.5	37.1
2	2584.9	377	37.7	
3	2651.8	370	37	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2536.6	468	46.8	47.4
2	2620.3	440	44	
3	2641.2	515	51.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	256.2	456	45.6	45.6
2	2574.9	465	46.5	
3	2285.9	446	44.6	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2560.3	453	45.3	46.2
2	2583.5	465	46.5	
3	2652.4	467	46.7	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2685.9	600	60	63.9
2	2590.6	637	63.7	
3	2643	680	68	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2448.7	510	51	57.0
2	2457	635	63.5	
3	2550	565	56.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2442.2	550	55	53.7
2	2537.2	522	52.2	
3	2553.2	540	54	

Concrete Strength Results for Cement D1

Cement D2	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2.6993	375	37.5	37.4
2	2.613	365	36.5	
3	2.63	382	38.2	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2.589	362	36.2	36.2
2	2.4473	345	34.5	
3	2.577	380	38	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2.4665	365	36.5	37.7
2	2.2549	378	37.8	
3	2.6289	389	38.9	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	0	400.1	40.01	42.8
2	0	433.8	43.38	
3	0	448.7	44.87	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	0	391.5	39.15	38.2
2	0	371.5	37.15	
3	0	382	38.2	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2.2572	437	43.7	43.1
2	2.4903	410	41	
3	2.5601	445	44.5	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2579.5	478	47.8	47.8
2	2633.9	477	47.7	
		Fair		
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2473.1	384	38.4	39.2
2	2650.7	400	40	
		Fsolar		
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2578.3	446	44.6	44.7
2	2561.7	448	44.8	

Concrete Strength Results for Cement D2

Cement E	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2605.4	245	24.5	26.0
2	2623.6	266	26.6	
3	2683.8	268	26.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2548.7	252	25.2	25.8
2	2589.7	260	26	
3	2533.2	262	26.2	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2419.2	273	27.3	26.8
2	2516.7	275	27.5	
3	2484.1	255	25.5	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2657	310	31	30.3
2	2513.5	280	28	
3	2570	320	32	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2349.5	342	34.2	34.1
2	2562.7	345	34.5	
3	2477.2	336	33.6	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2578.2	340	34	35.0
2	2497	361	36.1	
3	2242.7	349	34.9	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2716.7	447	44.7	45.1
2	2662.4	475	47.5	
3	2561.6	431	43.1	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2643.7	410	41	41.6
2	2462.1	417	41.7	
3	2508.6	420	42	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2480.1	464	46.4	46.5
2	2608.5	458	45.8	
3	2616.1	474	47.4	

Concrete Strength Results for Cement E

Cement F1	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2623	324	32.4	33.4
2	2606.8	337	33.7	
3	2612.9	340	34	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2498.3	355	35.5	35.1
2	2570.2	375	37.5	
3	2693.1	324	32.4	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2724.2	357	35.7	33.6
2	2652.7	322	32.2	
3	2613.1	330	33	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2682.8	368	36.8	35.1
2	2656.7	348	34.8	
3	2328.3	338	33.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2482.2	364	36.4	37.6
2	2788.8	355	35.5	
3	2716.4	408	40.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2669	414	41.4	41.3
2	2622.1	416	41.6	
3	2615	408	40.8	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	1713.4	371	37.1	38.8
2	1752	376	37.6	
3		417	41.7	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1		366	36.6	36.4
2		382	38.2	
3		344	34.4	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1		387	38.7	38.7
2				
3				

Concrete Strength Results for Cement F1

Cement G	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2514.5	365	36.5	37.1
2	2716.3	377	37.7	
3	2507.9	370	37	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2446	350	35	35.8
2	2527.4	369	36.9	41287.0
3	2594.9	355	35.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2605.8	333	33.3	33.0
2	2560.8	341	34.1	41298.0
3	2622.9	315	31.5	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2547.5	413	41.3	40.4
2	2687.1	403	40.3	
3	2511	395	39.5	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2624.4	392	39.2	38.6
2	2579.8	374	37.4	
3	2558.2	393	39.3	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2615.2	360	36	37.4
2	2444.9	387	38.7	
3	2612.2	374	37.4	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2538.7	457	45.7	47.4
2	2548.7	480	48	
3	2669.3	484	48.4	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2566.1	442	44.2	47.6
2	2421.1	487	48.7	
3	2592.1	498	49.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2562.7	490	49	47.3
2	2594.7	468	46.8	
3	2411.5	460	46	

Concrete Strength Results for Cement G

Cement H1	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2570.9	435	43.5	43.06666667
2	2588.6	439	43.9	
3	2641.4	418	41.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2605.8	405	40.5	42.16666667
2	2552	420	42	
3	2616.5	440	44	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2277.1	425	42.5	41.7
2	2319.2	420	42	
3	2506.5	406	40.6	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2416.2	534	53.4	54
2	2667.5	546	54.6	
3	2696.3	540	54	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2453.6	476	47.6	47.43333333
2	2567.4	485	48.5	
3		462	46.2	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2522.3	485	48.5	53.26666667
2	2464.8	553	55.3	
3	2560.1	560	56	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2666.8	807	80.7	76.3
2	2642.9	742	74.2	
3	2650.4	740	74	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2587.4	696	69.6	69.4
2	2531.9	692	69.2	
3				
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2553.9	785	78.5	78
2	2615	775	77.5	
3				

Concrete Strength Results for Cement H1

Cement H2	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2524	424	42.4	41
2	2697.8	418	41.8	
3	2616.1	388	38.8	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2527.2	408	40.8	40.26666667
2	2298.6	390	39	
3	2652.7	410	41	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2473.6	391	39.1	39.76666667
2	2594.4	412	41.2	
3	2563	390	39	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2622	510	51	50.16666667
2	2690.6	505	50.5	
3	2485	490	49	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2559.5	480	48	49.1
2	2658.3	503	50.3	
3	2304.2	490	49	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2995.8	550	55	53.16666667
2	2592.1	515	51.5	
3	2278	530	53	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2668	639	63.9	59.06666667
2	2618	642	64.2	
3	2670.1	491	49.1	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2553	535	53.5	54.36666667
2	2423.8	552	55.2	
3	2547	544	54.4	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2527.3	627	62.7	61.03333333
2	2582.4	586	58.6	
3	2532.3	618	61.8	

Concrete Strength Results for Cement H2

Cement I	4 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2692.9	482	48.2	44.7
2	2658.1	389	38.9	
3	2508.6	470	47	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2566.4	480	48	47.16666667
2	2292.2	485	48.5	
3	2616.8	450	45	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2533.2	465	46.5	45.16666667
2	2555.3	430	43	
3	2522	460	46	
	8 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2625.3	571	57.1	55.56666667
2	2622.3	536	53.6	
3	2579.5	560	56	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2576.3	500	50	51.73333333
2	2535.3	520	52	
3	2532.8	532	53.2	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2515.5	493	49.3	48.6
2	2581.9	475	47.5	
3	2636.8	490	49	
	29 Day			
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2686.2	600	60	64.23333333
2	2590.3	657	65.7	
3	2579.2	670	67	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1		nocube?		65.6
2	6368	655	65.5	
3	2582	657	65.7	
Specimen	Mass (g)	F water (KN)	Strength (Mpa)	Avg Strength (Mpa)
1	2547.3	610	61	55.1
2	2297	572	57.2	
3	2554.9	471	47.1	

Concrete Strength Results for Cement I

Appendix 4.2: Concrete Sorptivity Results

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	A1 Air						
Av. Sorptivity:	13.9	COV:	13.4				
Av. Porosity:	13.3	COV:	3.0				
Sample ID	51a11 p5	51a12p17	51a21p18	51a22p18			
Diameter 1 (mm)	69.11	68.91	69.04	68.95			
Diameter 2 (mm)	69.08	68.88	69.01	69.08			
Average Diameter (mm)	69.10	69.00	69.03	69.02			
Thickness 1 (mm)	30.68	27.46	30.43	30.55			
Thickness 2 (mm)	30.57	27.10	30.09	30.28			
Thickness 3 (mm)	30.15	27.22	29.96	30.38			
Thickness 4 (mm)	29.85	27.04	29.82	30.15			
Thickness (mm)	30.31	30.00	30.08	30.34			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	272.94	239.99	267.78	277.34			
3	274.33	241.60	269.30	278.43			
5	274.72	242.07	269.73	278.56			
7	275.00	242.45	270.08	278.72			
9	275.25	242.78	270.38	278.90			
12	275.58	243.24	270.94	279.30			
16	275.97	243.76	271.53	279.74			
20	276.33	244.23	271.97	280.09			
25	276.75	244.72	272.45	280.59			
Saturated Mass (g)	287.58	254.98	283.17	290.58			
R^2 (Must be >0.98)	0.9995	0.9995	0.9999	0.9999			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity ($mm/hr^{0.5}$)	11.7	14.9	15.0				
Porosity (%)	12.9	13.4	13.7				

Sorptivity Results for Cement A1 for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	A1 Solar						
Av. Sorptivity:	11.2	COV:	17.7				
Av. Porosity:	13.7	COV:	3.2				
Sample ID	51r11p3	51r12p18	51r21p18	51r22p18			
Diameter 1 (mm)	69.3	69.11	68.94	69.01			
Diameter 2 (mm)	69.25	68.98	69.19	69.01			
Average Diameter (mm)	69.28	69.05	69.07	69.01			
Thickness 1 (mm)	31.24	29.70	29.66	31.17			
Thickness 2 (mm)	31.55	29.82	29.46	31.46			
Thickness 3 (mm)	31.52	28.92	30.22	30.60			
Thickness 4 (mm)	30.65	29.50	30.26	30.15			
Thickness (mm)	31.24	29.49	29.90	30.85			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	272.85	264.18	267.04	273.10			
3	274.34	265.76	268.29	274.10			
5	274.75	266.23	268.63	274.40			
7	275.06	266.60	268.91	274.65			
9	275.35	266.93	269.15	274.87			
12	275.72	267.33	269.46	275.17			
16	276.14	267.79	269.82	275.51			
20	276.52	268.17	270.14	275.81			
25	276.96	268.59	270.50	276.14			
Saturated Mass (g)	289.01	278.70	282.43	289.52			
R^2 (Must be >0.98)	0.9999	0.9999	0.9991	0.9991			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	12.0	13.6	10.2	9.1			
Porosity (%)	13.7	13.2	13.7	14.2			

Sorptivity Results for Cement A1 for Curing in Solar Chamber

Samples Damaged During Sample Preparation-Discarded!

Sorptivity Results for Cement A1 for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	A2 Air						
Av. Sorptivity:	12.8	COV:	4.5				
Av. Porosity:	12.7	COV:	6.2				
Sample ID	52a11p5	52a12p16	52a21p16	52a22p16			
Diameter 1 (mm)	68.87	69.04	69.08	69.29			
Diameter 2 (mm)	69.04	69	69.1	69.24			
Average Diameter (mm)	68.96	69.02	69.09	69.27			
Thickness 1 (mm)	30.28	30.47	27.26	30.40			
Thickness 2 (mm)	31.53	30.66	27.66	29.78			
Thickness 3 (mm)	31.23	30.30	27.78	29.11			
Thickness 4 (mm)	30.26	29.62	27.26	30.10			
Thickness (mm)	30.83	30.26	27.49	29.85			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	272.60	277.57	241.74	271.50			
3	273.81	278.90	243.29	273.16			
5	274.16	279.22	243.66	273.56			
7	274.48	279.57	243.95	273.89			
9	274.75	279.82	244.17	274.15			
12	275.07	280.12	244.67	274.53			
16	275.48	280.52	245.24	274.97			
20	275.85	280.84	245.69	275.36			
25	276.27	281.20	246.17	275.77			
Saturated Mass (g)	287.14	291.04	255.96	285.73			
R^2 (Must be >0.98)	0.9996	0.9996	0.9994	0.9994			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	12.3	12.3	13.5	13.0			
Porosity (%)	12.6	11.9	13.8	12.7			

Sorptivity Results for Cement A2 for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	A2 Solar Chamber						
Av. Sorptivity:	12.7	COV:	12.5				
Av. Porosity:	12.6	COV:	16.5				
Sample ID	52r11p3	52r12p15	52r21p18	52r22p15			
Diameter 1 (mm)	68.93	69.04	68.94	69.08			
Diameter 2 (mm)	69	69.16	69.03	68.94			
Average Diameter (mm)	68.97	69.10	69.00	69.00			
Thickness 1 (mm)	29.83	30.42	30.83	30.20			
Thickness 2 (mm)	29.99	30.37	30.97	30.10			
Thickness 3 (mm)	30.27	29.77	30.55	30.20			
Thickness 4 (mm)	29.90	29.86	30.54	30.00			
Thickness (mm)	30.00	30.11	30.00	30.00			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	274.27	284.08	272.99	262.81			
3	275.95	285.13	274.12	264.86			
5	276.36	285.43	274.44	265.41			
7	276.72	285.69	274.72	265.85			
9	276.99	285.90	274.95	266.22			
12	277.31	286.19	275.26	266.53			
16	277.71	286.53	275.65	267.24			
20	278.04	286.80	275.97	267.72			
25	278.39	287.22	276.32	268.26			
Saturated Mass (g)	286.89	296.02	287.84	279.84			
R^2 (Must be >0.98)	0.9983	0.9983	0.9987	0.9987			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	13.7	12.3	10.6	14.1			
Porosity (%)	11.3	10.6	13.2	15.2			

Sorptivity Results for Cement A2 for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	A2 Water						
Av. Sorptivity:	10.4	COV:	4.8				
Av. Porosity:	11.9	COV:	8.9				
Sample ID	52w11p17	52w12p17	52w21*p13	52w22p14			
Diameter 1 (mm)	69.39	69.16	69.1	69.13			
Diameter 2 (mm)	69.1	69.16	69.15	69.14			
Average Diameter (mm)	69.25	69.16	69.13	69.14			
Thickness 1 (mm)	31.95	29.40	29.24	30.32			
Thickness 2 (mm)	33.98	28.18	29.36	30.22			
Thickness 3 (mm)	33.36	29.87	29.42	30.62			
Thickness 4 (mm)	31.00	31.51	29.46	30.27			
Thickness (mm)	32.57	29.74	29.37	30.36			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	295.70	277.56	269.67	279.03			
3	296.80	278.68	270.93	280.59			
5	297.10	278.98	271.27	280.96			
7	297.34	279.18	271.56	281.27			
9	297.55	279.35	271.79	281.50			
12	297.84	279.60	272.07	281.82			
16	298.15	279.87	272.42	282.16			
20	298.42	280.12	272.71	282.45			
25	298.73	280.33	273.05	282.77			
Saturated Mass (g)	310.24	289.43	282.96	294.08			
R^2 (Must be >0.98)	0.9999	0.9999	0.9986	0.9986			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	10.3	9.8	11.0	10.4			
Porosity (%)	11.9	10.6	12.1	13.2			

Sorptivity Results for Cement A2 for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	B Air						
Av. Sorptivity:	14.1	COV:	18.3				
Av. Porosity:	12.8	COV:	17.1				
Sample ID	4A11	44A12	44A21	44A22			
Diameter 1 (mm)	69.86	68.91	69.1	69.03			
Diameter 2 (mm)	69.87	69.1	69.19	69.07			
Average Diameter (mm)	69.87	69.01	69.15	69.05			
Thickness 1 (mm)	30.10	31.26	32.05	22.08			
Thickness 2 (mm)	30.12	30.31	30.70	29.26			
Thickness 3 (mm)	29.70	30.02	30.22	29.67			
Thickness 4 (mm)	29.50	30.61	32.18	29.48			
Thickness (mm)	29.86	30.55	31.29	27.62			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	262.37	283.28	281.02	257.90			
3	264.23	284.57	282.19	259.68			
5	264.70	285.01	282.54	260.51			
7	265.10	285.38	282.83	260.93			
9	265.42	285.70	283.06	261.26			
12	265.84	286.14	283.37	261.69			
16	266.31	286.66	283.65	262.23			
20	266.74	287.11	283.92	262.71			
25	267.15	287.62	284.18	263.23			
Saturated Mass (g)	277.53	295.90	294.05	274.07			
R^2 (Must be >0.98)	0.9993	0.9993	0.9996	0.9996			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	13.7	17.6	11.3	13.8			
Porosity (%)	13.2	11.0	11.1	15.6			

Sorptivity Results for Cement B for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	B Solar						
Av. Sorptivity:	Invalid	COV:	#VALUE!				
Av. Porosity:	11.7	COV:	5.6				
Sample ID		44R12	44R21	44R22			
Diameter 1 (mm)		68.97	68.98	68.91			
Diameter 2 (mm)		69.03	69.05	68.92			
Average Diameter (mm)		69.00	69.02	68.92			
Thickness 1 (mm)		31.75	30.90	30.79			
Thickness 2 (mm)		30.64	30.24	31.38			
Thickness 3 (mm)		30.75	30.50	30.24			
Thickness 4 (mm)		30.38	30.78	29.59			
Thickness (mm)		30.88	30.61	30.50			
Time (min)		Mass (g)	Mass (g)	Mass (g)			
0		283.11	273.87	282.15			
3		284.57	275.25	283.42			
5		285.02	275.68	283.78			
7		285.40	276.00	284.03			
9		285.70	276.25	284.24			
12		286.11	276.55	284.50			
16		286.55	276.93	284.80			
20		286.91	277.23	285.02			
25		287.30	277.57	285.29			
Saturated Mass (g)		295.97	288.1	295.34			
R^2 (Must be >0.98)	#DIV/0!	#DIV/0!	#DIV/0!	0.9985			
Range	#DIV/0!	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)		15.6	11.7	10.1			
Porosity (%)		11.1	12.4	11.6			

Sorptivity Results for Cement B for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	B Water						
Av. Sorptivity:	7.7						
Av. Porosity:	13.0						
Sample ID	44w11	44w12					
Diameter 1 (mm)	69.4	69.12					
Diameter 2 (mm)	69.1	69.28					
Average Diameter (mm)	69.25	69.20					
Thickness 1 (mm)	30.90	29.40					
Thickness 2 (mm)	30.60	29.92					
Thickness 3 (mm)	30.28	30.26					
Thickness 4 (mm)	30.60	29.83					
Thickness (mm)	30.60	29.85					
Time (min)	Mass (g)	Mass (g)					
0	279.18	266.26					
3	280.04	267.34					
5	280.29	267.58					
7	280.50	267.78					
9	280.67	267.94					
12	280.91	268.14					
16	281.22	268.37					
20	281.44	268.58					
25	281.76	268.81					
Saturated Mass (g)	293.48	281.56					
R^2 (Must be >0.98)	0.9991	0.9991					
Range	3-25 min	3-25 min					
Sorptivity (mm/hr$^{0.5}$)	8.7	6.8					
Porosity (%)	12.4	13.6					

Sorptivity Results for Cement B for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	C Air						
Av. Sorptivity:	14.4	COV:	41.8				
Av. Porosity:	16.7	COV:	21.9				
Sample ID	42a11 bad p 5	42a12*p12	42a21p11				
Diameter 1 (mm)	68.88	69.04	69.39				
Diameter 2 (mm)	69	69.1	69.25				
Average Diameter (mm)	68.94	69.07	69.32				
Thickness 1 (mm)	31.66	31.08	29.25				
Thickness 2 (mm)	32.32	30.60	29.21				
Thickness 3 (mm)	30.60	31.12	29.40				
Thickness 4 (mm)	31.44	30.58	29.25				
Thickness (mm)	31.51	30.85	29.28				
Time (min)	Mass (g)	Mass (g)	Mass (g)				
0	260.49	266.69	262.72				
3	264.34	269.26	264.09				
5	265.28	269.93	264.40				
7	266.04	270.48	264.61				
9	266.70	270.99	264.81				
12	267.60	271.64	265.04				
16	268.57	272.41	265.28				
20	269.42	273.12	265.50				
25	270.35	273.32	265.73				
Saturated Mass (g)	284.88	284.88	277.78				
R^2 (Must be >0.98)	0.9999	0.9999	0.9905				
Range	3-25 min	3-25 min	3-25 min				
Sorptivity (mm/hr$^{0.5}$)	18.5	17.3	7.5				
Porosity (%)	20.7	15.7	13.6				

Sorptivity Results for Cement C for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	C Solar						
Av. Sorptivity:	19.5	COV:	4.1				
Av. Porosity:	15.7	COV:	4.3				
Sample ID		42r12p12	42r21p12	42r22*p12			
Diameter 1 (mm)		69.12	68.93	69.12			
Diameter 2 (mm)		69.05	69.08	69.02			
Average Diameter (mm)		69.09	69.01	69.07			
Thickness 1 (mm)		30.38	30.82	30.26			
Thickness 2 (mm)		29.54	30.48	30.12			
Thickness 3 (mm)		30.39	30.42	29.84			
Thickness 4 (mm)		30.88	30.70	30.28			
Thickness (mm)		30.30	30.61	30.13			
Time (min)		Mass (g)	Mass (g)	Mass (g)			
0		264.46	272.46	248.76			
3		267.71	275.21	251.77			
5		268.46	275.89	252.51			
7		269.09	276.44	253.17			
9		269.65	276.93	253.74			
12		270.32	277.58	254.46			
16		271.13	278.34	255.30			
20		271.81	278.99	256.02			
25		272.55	279.72	256.81			
Saturated Mass (g)		282.99	289.59	266.56			
R^2 (Must be >0.98)		0.9999	0.9998	0.9998			
Range		3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)		18.8	19.2	20.4			
Porosity (%)		16.3	15.0	15.8			

Sorptivity Results for Cement C for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	C Water						
Av. Sorptivity:	10.0	COV:	31.8				
Av. Porosity:	14.5	COV:	18.3				
Sample ID	42w11p1	42w12p11	42w21p11	42w22p11			
Diameter 1 (mm)	69.11	69.15	69.14	69.02			
Diameter 2 (mm)	69.19	69.18	68.47	69.14			
Average Diameter (mm)	69.15	69.17	68.81	69.08			
Thickness 1 (mm)	32.42	29.42	34.72	31.84			
Thickness 2 (mm)	30.72	30.22	35.56	30.74			
Thickness 3 (mm)	31.30	29.03	34.07	30.88			
Thickness 4 (mm)	31.86	28.53	34.51	32.12			
Thickness (mm)	31.58	29.30	34.72	31.40			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	285.37	255.73	316.82	284.98			
3	286.61	257.68	318.08	286.63			
5	286.89	258.09	318.41	287.04			
7	287.11	258.38	318.69	287.39			
9	287.31	258.62	318.93	287.69			
12	287.53	258.92	319.22	288.08			
16	287.80	259.25	319.61	288.54			
20	288.04	259.55	319.94	288.96			
25	288.34	259.86	320.34	289.42			
Saturated Mass (g)	303.37	275.52	332.17	300.45			
R^2 (Must be >0.98)	0.9995	0.9995	0.9975	0.9975			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	7.1	7.6	12.1	13.4			
Porosity (%)	15.2	18.0	11.9	13.1			

Sorptivity Results for Cement C for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	D1 Air						
Av. Sorptivity:	12.7	COV:	10.2				
Av. Porosity:	13.2	COV:	3.4				
Sample ID	54a11p3	54a12p16	54a21p16	54a22p16			
Diameter 1 (mm)	68.9	68.9	69.1	69.02			
Diameter 2 (mm)	68.88	69.1	68.96	69.14			
Average Diameter (mm)	68.89	69.00	69.03	69.08			
Thickness 1 (mm)	30.72	30.34	30.76	30.18			
Thickness 2 (mm)	30.64	30.23	29.81	30.01			
Thickness 3 (mm)	30.51	30.00	30.20	30.16			
Thickness 4 (mm)	30.20	30.20	30.81	29.58			
Thickness (mm)	30.52	30.19	30.40	29.98			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	275.41	272.43	278.02	267.13			
3	277.05	274.21	279.25	268.90			
5	277.50	274.65	279.60	269.38			
7	277.86	275.00	279.88	269.75			
9	278.17	275.29	280.10	270.07			
12	278.58	275.65	280.42	270.48			
16	279.01	276.09	280.80	270.96			
20	279.42	276.46	281.11	271.35			
25	279.87	276.88	281.48	271.79			
Saturated Mass (g)	290.13	287.01	292.76	282.67			
R^2 (Must be >0.98)	0.9998	0.9998	0.9997	0.9997			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	13.8	13.0	10.9	13.2			
Porosity (%)	12.9	12.9	13.0	13.8			

Sorptivity Results for Cement D1 for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	D1 Solar						
Av. Sorptivity:	11.2	COV:	6.2				
Av. Porosity:	12.2	COV:	7.8				
Sample ID	54r11p3	54r12p18	54r21p18	54r22p18			
Diameter 1 (mm)	69	69.01	69.06	69.07			
Diameter 2 (mm)	69.15	68.98	69.1	69.12			
Average Diameter (mm)	69.08	69.00	68.00	69.00			
Thickness 1 (mm)	29.98	31.04	29.61	30.28			
Thickness 2 (mm)	29.93	31.21	29.30	30.30			
Thickness 3 (mm)	29.95	31.26	29.49	30.85			
Thickness 4 (mm)	29.58	31.15	30.10	30.83			
Thickness (mm)	29.86	30.00	30.00	30.00			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	269.25	290.95	266.60	285.79			
3	270.49	292.24	267.99	287.15			
5	270.81	292.57	268.33	287.52			
7	271.06	292.84	268.61	287.79			
9	271.26	293.07	268.85	288.03			
12	271.59	293.35	269.15	288.34			
16	271.95	293.69	269.51	288.68			
20	272.27	293.99	269.81	288.99			
25	272.64	294.32	270.15	289.31			
Saturated Mass (g)	283.77	303.71	280.81	298.54			
R^2 (Must be >0.98)	0.9992	0.9992	0.9999	0.9999			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	10.5	11.6	10.8	12.0			
Porosity (%)	13.0	11.4	13.0	11.4			

Sorptivity Results for Cement D1 for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	D1 Water						
Av. Sorptivity:	12.6	COV:	7.4				
Av. Porosity:	12.5	COV:	8.2				
Sample ID	54w11p17	54w12p16	54w21p16	54w22p16			
Diameter 1 (mm)	69.32	69.15	69.2	69.28			
Diameter 2 (mm)	69.28	69.26	69.18	69.15			
Average Diameter (mm)	69.30	69.21	69.19	69.22			
Thickness 1 (mm)	28.47	29.54	29.91	29.17			
Thickness 2 (mm)	28.02	29.70	29.60	29.44			
Thickness 3 (mm)	28.40	29.92	29.40	29.74			
Thickness 4 (mm)	28.34	29.29	29.40	29.79			
Thickness (mm)	28.31	29.61	29.58	29.54			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	265.44	263.52	269.53	271.95			
3	266.53	265.25	271.11	273.53			
5	266.84	265.69	271.54	273.93			
7	267.12	266.06	271.90	274.24			
9	267.34	266.38	272.20	274.50			
12	267.64	266.77	272.61	274.84			
16	268.01	267.24	273.07	275.21			
20	268.28	267.65	273.45	275.52			
25	268.64	268.07	273.87	275.82			
Saturated Mass (g)	277.46	278.76	283.67	285.45			
R^2 (Must be >0.98)	0.9998	0.9998	0.9998	0.9998			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	11.8	13.0	13.8	11.9			
Porosity (%)	11.3	13.7	12.7	12.1			

Sorptivity Results for Cement D1 for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	D2 Air						
Av. Sorptivity:	12.4	COV:	1.8				
Av. Porosity:	12.5	COV:	5.3				
Sample ID	31a11p8	31a12	31a21p14	31a22p13			
Diameter 1 (mm)	69	69.02	69.06	69.2			
Diameter 2 (mm)	69.26	69.02	69.11	69.12			
Average Diameter (mm)	69.13	69.02	69.09	69.16			
Thickness 1 (mm)	29.57	30.42	32.40	30.23			
Thickness 2 (mm)	30.20	30.58	32.20	29.90			
Thickness 3 (mm)	30.32	30.22	31.82	29.89			
Thickness 4 (mm)	30.16	30.05	30.56	29.91			
Thickness (mm)	30.06	30.32	31.75	29.98			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	273.40	280.84	287.33	273.38			
3	274.93	281.82	288.77	274.84			
5	275.34	282.21	289.21	275.22			
7	275.66	282.65	289.50	275.54			
9	275.96	282.94	289.69	275.83			
12	276.25	283.18	290.04	276.21			
16	276.66	283.47	290.43	276.67			
20	277.06	283.85	290.78	277.07			
25	277.40	284.25	292.17	277.53			
Saturated Mass (g)	287.39	294.48	301.91	288.6			
R^2 (Must be >0.98)	0.9990	0.9990	0.9916	0.9916			
Range	3-25 min	3-25 min	3-25 min	3-20 min			
Sorptivity (mm/hr$^{0.5}$)	12.6	12.4	12.1	12.6			
Porosity (%)	12.4	12.0	12.3	13.5			

Sorptivity Results for Cement D2 for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	D2 Solar						
Av. Sorptivity:	12.9	COV:	12.8				
Av. Porosity:	14.7	COV:	6.7				
Sample ID	31r11p9bump	31r12p14	31r21p4 6c	31r22p13			
Diameter 1 (mm)	68.95	68.9	69.02	69.16			
Diameter 2 (mm)	68.98	68.99	69.01	69.24			
Average Diameter (mm)	68.97	68.95	69.02	69.20			
Thickness 1 (mm)	30.53	29.90	30.07	30.76			
Thickness 2 (mm)	29.56	29.43	29.38	30.68			
Thickness 3 (mm)	29.47	30.62	29.18	30.24			
Thickness 4 (mm)	30.90	30.28	29.17	30.68			
Thickness (mm)	30.12	30.06	29.45	30.59			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	265.93	264.68	261.17	280.90			
3	267.73	266.53	262.96	282.32			
5	268.28	267.07	263.43	282.69			
7	268.71	267.52	263.86	282.97			
9	269.09	267.88	264.15	283.23			
12	269.55	268.36	264.58	283.54			
16	270.08	268.90	265.09	283.90			
20	270.56	269.38	265.54	284.21			
25	271.08	269.92	266.03	284.54			
Saturated Mass (g)	282.7	281.99	277.83	296.14			
R^2 (Must be >0.98)	0.9997	0.9997	0.9998	0.9998			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	14.2	13.9	12.8	10.6			
Porosity (%)	14.9	15.4	15.1	13.2			

Sorptivity Results for Cement D2 for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	D2 Water						
Av. Sorptivity:	9.4	COV:	15.6				
Av. Porosity:	14.0	COV:	8.5				
Sample ID	31w11p10	31w12p13	31w21p13	31w22p14			
Diameter 1 (mm)	69.1	69.24	69.31	69.28			
Diameter 2 (mm)	69.32	69.05	69.04	69.14			
Average Diameter (mm)	69.21	69.15	69.18	69.21			
Thickness 1 (mm)	31.82	31.40	28.92	29.36			
Thickness 2 (mm)	31.56	30.48	29.90	29.25			
Thickness 3 (mm)	31.36	30.49	29.28	29.57			
Thickness 4 (mm)	31.28	31.56	28.68	29.60			
Thickness (mm)	31.51	30.98	29.20	29.45			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	282.98	288.08	267.24	262.36			
3	284.52	289.06	268.44	263.58			
5	284.94	289.33	268.75	263.90			
7	285.28	289.53	269.04	264.17			
9	285.54	289.70	269.28	264.38			
12	285.90	289.92	269.60	264.67			
16	286.31	290.20	269.96	265.03			
20	286.63	290.43	270.28	265.33			
25	287.01	290.70	270.64	265.65			
Saturated Mass (g)	300	303.14	281.83	279.63			
R^2 (Must be >0.98)	0.9991	0.9991	0.9998	0.9998			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	10.9	7.9	10.5	8.4			
Porosity (%)	14.4	12.9	13.3	15.6			

Sorptivity Results for Cement D2 for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	E Air						
Av. Sorptivity:	12.4	COV:	14.5				
Av. Porosity:	14.1	COV:	1.7				
Sample ID	32a11p8	32a12	32a21*p13				
Diameter 1 (mm)	68.88	69.07	69.28				
Diameter 2 (mm)	69.2	69.1	69.15				
Average Diameter (mm)	69.04	69.09	69.22				
Thickness 1 (mm)	30.98	30.28	27.40				
Thickness 2 (mm)	29.88	30.78	28.02				
Thickness 3 (mm)	29.46	30.14	28.10				
Thickness 4 (mm)	30.66	30.04	28.00				
Thickness (mm)	30.25	30.31	27.88				
Time (min)	Mass (g)	Mass (g)	Mass (g)				
0	268.59	273.99	252.49				
3	269.15	275.36	254.01				
5	269.55	275.82	254.38				
7	269.90	276.20	254.67				
9	270.23	276.53	254.90				
12	270.63	276.97	255.22				
16	271.12	277.48	255.61				
20	271.52	277.94	255.95				
25	271.99	278.45	256.35				
Saturated Mass (g)	284.84	289.83	267.12				
R^2 (Must be >0.98)	0.9998	0.9998	0.9999				
Range	3-25 min	3-25 min	3-25 min				
Sorptivity (mm/hr$^{0.5}$)	12.6	14.0	10.5				
Porosity (%)	14.4	13.9	13.9				

Sorptivity Results for Cement E for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	E Solar						
Av. Sorptivity:	13.4						
Av. Porosity:	13.6						
Sample ID	32r11p9						
Diameter 1 (mm)	69.6	68.9					
Diameter 2 (mm)	69.5	68.8					
Average Diameter (mm)	69.55	68.85					
Thickness 1 (mm)	30.46	31.28					
Thickness 2 (mm)	30.42	30.23					
Thickness 3 (mm)	30.14	31.03					
Thickness 4 (mm)	30.85	31.10					
Thickness (mm)	30.47	30.91					
Time (min)	Mass (g)	Mass (g)					
0	276.27	285.44					
3	277.90	286.92					
5	278.36	287.36					
7	278.74	287.72					
9	279.05	288.03					
12	279.46	288.42					
16	279.95	288.89					
20	280.35	289.28					
25	280.85	289.74					
Saturated Mass (g)	292.63	300.38					
R^2 (Must be >0.98)	0.9999	0.9999					
Range	3-25 min	3-25 min					
Sorptivity (mm/hr$^{0.5}$)	13.0	13.8					
Porosity (%)	14.1	13.0					

Sorptivity Results for Cement E for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	E Water						
Av. Sorptivity:	10.5						
Av. Porosity:	13.9						
Sample ID			32w21	32w2 p 14			
Diameter 1 (mm)			69.22	69.1			
Diameter 2 (mm)			69.38	69.31			
Average Diameter (mm)			69.30	69.21			
Thickness 1 (mm)			30.16	30.08			
Thickness 2 (mm)			30.09	30.06			
Thickness 3 (mm)			30.62	29.96			
Thickness 4 (mm)			30.78	30.20			
Thickness (mm)			30.41	30.08			
Time (min)			Mass (g)	Mass (g)			
0			281.45	269.99			
3			282.72	271.67			
5			283.05	272.07			
7			283.31	272.40			
9			283.50	272.69			
12			283.81	273.06			
16			284.15	273.47			
20			284.46	273.85			
25			284.79	274.27			
Saturated Mass (g)			296.37	286.65			
R^2 (Must be >0.98)			0.9971	0.9971			
Range			3-25 min	3-25 min			
Sorptivity ($mm/hr^{0.5}$)			10.0	11.1			
Porosity (%)			13.0	14.7			

Sorptivity Results for Cement E for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	F1 A						
Av. Sorptivity:	12.5						
Av. Porosity:	12.7						
Sample ID			43a21*p12	43a22			
Diameter 1 (mm)			69.08	69.16			
Diameter 2 (mm)			69.4	68.99			
Average Diameter (mm)			69.24	69.08			
Thickness 1 (mm)			28.05	28.80			
Thickness 2 (mm)			27.80	30.29			
Thickness 3 (mm)			28.08	31.07			
Thickness 4 (mm)			28.00	29.95			
Thickness (mm)			27.98	30.03			
Time (min)			Mass (g)	Mass (g)			
0			273.80	276.24			
3			275.48	277.62			
5			275.93	278.04			
7			276.29	278.38			
9			276.62	278.68			
12			277.03	279.03			
16			277.50	279.46			
20			277.68	279.71			
25			277.83	279.86			
Saturated Mass (g)			287.88	289.84			
R^2 (Must be >0.98)			0.9971	0.9971			
Range			3-25 min	3-20 min			
Sorptivity ($mm/hr^{0.5}$)			12.8	12.2			
Porosity (%)			13.4	12.1			

Sorptivity Results for Cement F1 for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	F1 Solar						
Av. Sorptivity:	14.3	COV:	6.7				
Av. Porosity:	13.2	COV:	5.6				
Sample ID	43r11p6	43r12p11	43r21p11	43r22p11			
Diameter 1 (mm)	68.98	69.35	68.92	69.06			
Diameter 2 (mm)	69	69.04	68.86	68.89			
Average Diameter (mm)	68.99	69.00	68.00	69.00			
Thickness 1 (mm)	30.07	30.06	30.32	30.95			
Thickness 2 (mm)	30.30	30.05	30.30	30.77			
Thickness 3 (mm)	31.04	29.92	30.05	30.35			
Thickness 4 (mm)	30.07	29.71	29.97	30.30			
Thickness (mm)	30.37	30.00	30.00	30.00			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	277.34	280.16	278.87	282.47			
3	279.65	281.57	280.77	283.90			
5	280.21	281.93	281.33	284.33			
7	280.64	282.24	281.72	284.67			
9	281.01	282.52	282.07	284.99			
12	281.50	282.90	282.49	285.41			
16	282.02	283.33	282.97	285.89			
20	282.30	283.71	283.38	286.31			
25	283.04	284.14	283.83	286.82			
Saturated Mass (g)	292.46	293.90	294.17	297.35			
R^2 (Must be >0.98)	0.9962	0.9962	0.9996	0.9996			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	15.6	13.4	14.1	13.9			
Porosity (%)	13.3	12.2	14.0	13.3			

Sorptivity Results for Cement F1 for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	F1 Water						
Av. Sorptivity:	12.1	COV:	7.3				
Av. Porosity:	13.0	COV:	10.3				
Sample ID	43w11p1	43w12p17	43w21p11	3w22p11bad			
Diameter 1 (mm)	69.24	69.14	69.45	69.28			
Diameter 2 (mm)	69.34	69.29	69.2	69.15			
Average Diameter (mm)	69.29	69.22	69.33	69.22			
Thickness 1 (mm)	31.71	28.10	29.33	27.48			
Thickness 2 (mm)	31.70	27.29	28.48	28.18			
Thickness 3 (mm)	30.26	27.37	28.37	28.80			
Thickness 4 (mm)	30.29	27.95	28.82	27.92			
Thickness (mm)	30.99	27.68	28.75	28.10			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	289.65	256.70	265.02	249.43			
3	290.99	258.03	266.42	251.47			
5	291.34	258.44	266.81	251.93			
7	291.62	258.72	267.11	252.30			
9	291.85	259.02	267.36	252.59			
12	292.16	259.39	267.70	252.99			
16	292.51	259.82	268.08	253.46			
20	292.83	260.20	268.42	253.85			
25	293.20	260.60	268.80	254.29			
Saturated Mass (g)	303.23	269.48	279.55	264.95			
R^2 (Must be >0.98)	0.9999	0.9999	0.9998	0.9998			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	11.9	13.2	11.1	12.1			
Porosity (%)	11.6	12.3	13.4	14.7			

Sorptivity Results for Cement F1 for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	G Air						
Av. Sorptivity:	14.8	COV:	11.1				
Av. Porosity:	12.0	COV:	5.6				
Sample ID	41a11p1	41a12p12	41a21p12	41a22*p12			
Diameter 1 (mm)	68.8	68.94	69	69.1			
Diameter 2 (mm)	68.88	68.97	69.18	69.25			
Average Diameter (mm)	70.00	70.00	70.00	70.00			
Thickness 1 (mm)	29.60	30.33	30.16	29.50			
Thickness 2 (mm)	29.36	30.14	30.11	28.68			
Thickness 3 (mm)	29.10	29.89	30.91	28.85			
Thickness 4 (mm)	29.29	30.10	30.23	28.99			
Thickness (mm)	32.00	32.00	32.00	32.00			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	269.55	271.49	278.55	264.37			
3	271.22	273.12	280.40	266.02			
5	271.70	273.54	280.97	266.53			
7	272.04	273.86	281.42	266.88			
9	272.35	274.14	281.81	267.22			
12	272.70	274.50	282.30	267.62			
16	273.13	274.93	282.86	268.06			
20	273.52	275.29	283.32	268.44			
25	273.96	275.70	283.84	268.87			
Saturated Mass (g)	283.15	286.69	294.03	279.08			
R^2 (Must be >0.98)	0.9992	0.9992	0.9999	0.9999			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	15.0	12.8	16.8	14.6			
Porosity (%)	11.0	12.3	12.6	11.9			

Sorptivity Results for Cement G for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	G Solar						
Av. Sorptivity:	12.6						
Av. Porosity:	11.8						
Sample ID			41r21p11	41r22p11			
Diameter 1 (mm)			68.95	68.96			
Diameter 2 (mm)			68.92	69.06			
Average Diameter (mm)			68.94	69.01			
Thickness 1 (mm)			29.64	31.16			
Thickness 2 (mm)			29.42	29.95			
Thickness 3 (mm)			29.62	30.62			
Thickness 4 (mm)			30.10	30.47			
Thickness (mm)			29.70	30.55			
Time (min)			Mass (g)	Mass (g)			
0			271.21	281.55			
3			272.69	282.68			
5			273.08	283.00			
7			273.41	283.25			
9			273.67	283.46			
12			274.04	283.77			
16			274.47	284.12			
20			274.86	284.43			
25			275.30	284.79			
Saturated Mass (g)			285.23	294.14			
R^2 (Must be >0.98)			0.9971	0.9971			
Range			3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)			13.1	12.1			
Porosity (%)			12.7	11.0			

Sorptivity Results for Cement G for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	G Water						
Av. Sorptivity:	11.9	COV:	10.4				
Av. Porosity:	12.8	COV:	6.9				
Sample ID	41w11p1	41w12p12	41w21p12	41w22p12			
Diameter 1 (mm)	69.19	69.08	69.1	69.1			
Diameter 2 (mm)	69.26	69.29	69.38	69.12			
Average Diameter (mm)	69.23	69.19	69.24	69.11			
Thickness 1 (mm)	29.76	29.77	30.71	28.92			
Thickness 2 (mm)	29.48	30.40	30.08	29.48			
Thickness 3 (mm)	29.54	30.00	29.92	29.38			
Thickness 4 (mm)	29.84	30.10	30.21	28.83			
Thickness (mm)	29.66	30.07	30.23	29.15			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	259.99	277.97	272.90	267.14			
3	261.71	279.22	274.60	268.44			
5	262.15	279.54	275.02	268.74			
7	262.53	279.82	275.37	269.00			
9	262.83	280.01	275.63	269.22			
12	263.23	280.29	275.98	269.52			
16	263.70	280.62	276.39	269.86			
20	264.11	281.14	276.83	270.11			
25	264.59	281.53	277.17	270.41			
Saturated Mass (g)	275.5	291.35	287.7	280.69			
R^2 (Must be >0.98)	1.0000	1.0000	0.9909	0.9909			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	13.0	12.2	12.5	10.1			
Porosity (%)	13.9	11.8	13.0	12.4			

Sorptivity Results for Cement G for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	H1 Air						
Av. Sorptivity:	11.9	COV:	3.4				
Av. Porosity:	12.1	COV:	5.2				
Sample ID	34a11p8chip	34a12p14	34a21	34a22p15			
Diameter 1 (mm)	69.5	68.98	69.03	68.92			
Diameter 2 (mm)	68.94	69.05	68.94	68.99			
Average Diameter (mm)	69.22	69.02	68.99	68.96			
Thickness 1 (mm)	29.93	30.60	30.36	30.69			
Thickness 2 (mm)	29.34	29.88	29.83	30.30			
Thickness 3 (mm)	29.16	29.91	29.90	30.62			
Thickness 4 (mm)	29.86	30.32	30.28	31.02			
Thickness (mm)	29.57	30.18	30.09	30.66			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	271.68	277.76	270.72	287.92			
3	272.05	279.14	272.32	289.09			
5	272.39	279.49	272.71	289.40			
7	272.67	279.80	273.02	289.67			
9	272.91	280.05	273.27	289.89			
12	273.23	280.40	273.40	290.02			
16	273.62	280.81	274.01	290.53			
20	273.98	281.16	274.31	290.80			
25	274.37	281.53	274.67	291.11			
Saturated Mass (g)	285.7	291.7	284.62	300.75			
R^2 (Must be >0.98)	0.9994	0.9994	0.9999	0.9999			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	11.6	12.4	12.0	11.5			
Porosity (%)	12.6	12.3	12.4	11.2			

Sorptivity Results for Cement H1 for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	H1 Solar						
Av. Sorptivity:	11.9	COV:	3.5				
Av. Porosity:	12.3	COV:	7.8				
Sample ID	34r11p13	34r12p14	34r21p14	34r22p13			
Diameter 1 (mm)	68.96	68.99	69.06	69.09			
Diameter 2 (mm)	68.91	68.98	69.04	69.41			
Average Diameter (mm)	68.94	68.99	69.05	69.25			
Thickness 1 (mm)	29.24	30.42	29.92	28.63			
Thickness 2 (mm)	29.47	30.22	29.84	29.35			
Thickness 3 (mm)	30.50	29.74	30.98	29.27			
Thickness 4 (mm)	30.30	29.80	31.18	29.22			
Thickness (mm)	29.88	30.05	30.48	29.12			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	269.92	278.99	283.78	260.69			
3	271.75	280.48	285.13	262.25			
5	272.17	280.88	285.46	262.68			
7	272.50	281.16	285.69	263.00			
9	272.77	281.41	285.93	263.28			
12	273.12	281.75	286.20	263.65			
16	273.50	282.13	286.52	264.07			
20	273.86	282.42	286.82	264.43			
25	274.21	282.77	287.15	264.82			
Saturated Mass (g)	283.97	292.58	296.55	275.5			
R^2 (Must be >0.98)	0.9989	0.9989	0.9991	0.9991			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	12.4	12.0	11.4	12.0			
Porosity (%)	12.6	12.1	11.2	13.5			

Sorptivity Results for Cement H1 for Curing in Solar Chamber

Samples Damaged During Sample Preparation- Discarded

Sorptivity Results for Cement H1 for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	H2 Air						
Av. Sorptivity:	21.8	COV:	6.3				
Av. Porosity:	14.8	COV:	9.7				
Sample ID	35A11	35A12	35A21	35A22			
Diameter 1 (mm)	68.96	69.14	69.09	69.05			
Diameter 2 (mm)	68.95	69.23	69.1	69.02			
Average Diameter (mm)	68.96	69.19	69.10	69.04			
Thickness 1 (mm)	27.28	31.30	30.60	29.81			
Thickness 2 (mm)	28.00	30.80	30.92	29.95			
Thickness 3 (mm)	27.38	31.15	30.57	29.64			
Thickness 4 (mm)	29.60	30.97	30.43	29.60			
Thickness (mm)	28.07	31.06	30.63	29.75			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	239.04	274.91	260.66	273.63			
3	241.69	276.59	263.76	276.19			
5	242.50	277.13	264.65	276.95			
7	243.17	277.59	265.38	277.56			
9	243.73	278.00	266.00	278.09			
12	244.52	278.58	266.82	278.99			
16	245.44	279.28	267.77	279.64			
20	246.31	279.92	268.60	280.39			
25	247.25	280.65	269.53	281.21			
Saturated Mass (g)	255.8	289.83	278.57	290.14			
R^2 (Must be >0.98)	0.9994	0.9994	0.9978	0.9978			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	22.1	20.1	23.4	21.5			
Porosity (%)	16.0	12.8	15.6	14.8			

Sorptivity Results for Cement H2 for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	H2 Solar						
Av. Sorptivity:	15.0	COV:	54.1				
Av. Porosity:	14.5	COV:	827.7				
Sample ID	35R11	35R12	35R21	35R22			
Diameter 1 (mm)	68.9	68.98	68.97	69.02			
Diameter 2 (mm)	69.2	68.94	69.19	69.18			
Average Diameter (mm)	69.05	68.96	69.08	69.10			
Thickness 1 (mm)	28.27	29.81	30.99	29.86			
Thickness 2 (mm)	29.18	29.67	30.55	29.66			
Thickness 3 (mm)	28.03	29.26	30.85	28.78			
Thickness 4 (mm)	28.37	28.98	30.79	28.37			
Thickness (mm)	28.46	29.43	30.80	29.17			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	2.67	260.40	268.62	261.20			
3	268.08	262.01	270.65	263.14			
5	268.36	262.43	271.22	263.65			
7	268.56	262.76	271.67	264.06			
9	268.76	263.02	272.05	264.42			
12	269.02	263.39	272.54	264.87			
16	269.30	263.78	273.14	265.40			
20	269.57	264.16	273.68	265.87			
25	269.86	264.53	274.28	266.40			
Saturated Mass (g)	10	10.00	285.88	276.54			
R^2 (Must be >0.98)	0.9998	0.9998	0.9996	0.9996			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	16.4	-0.7	15.3	14.7			
Porosity (%)	6.9	-227.8	15.0	14.0			

Sorptivity Results for Cement H2 for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	H2 Water						
Av. Sorptivity:	6.6						
Av. Porosity:	13.7						
Sample ID			35W21				
Diameter 1 (mm)			68.8				
Diameter 2 (mm)			68.94				
Average Diameter (mm)			68.87				
Thickness 1 (mm)			28.96				
Thickness 2 (mm)			28.50				
Thickness 3 (mm)			28.70				
Thickness 4 (mm)			28.44				
Thickness (mm)			28.65				
Time (min)			Mass (g)				
0			266.28				
3			267.14				
5			267.37				
7			267.55				
9			267.69				
12			267.88				
16			268.12				
20			268.34				
25			268.58				
Saturated Mass (g)			280.95				
R^2 (Must be >0.98)			0.9971				
Range			3-25 min				
Sorptivity ($mm/hr^{0.5}$)			6.6				
Porosity (%)			13.7				

Sorptivity Results for Cement H2 for Curing in Water

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	I Air						
Av. Sorptivity:	12.7	COV:	10.2				
Av. Porosity:	13.2	COV:	3.4				
Sample ID	54a11p3	54a12p16	54a21p16	54a22p16			
Diameter 1 (mm)	68.9	68.9	69.1	69.02			
Diameter 2 (mm)	68.88	69.1	68.96	69.14			
Average Diameter (mm)	68.89	69.00	69.03	69.08			
Thickness 1 (mm)	30.72	30.34	30.76	30.18			
Thickness 2 (mm)	30.64	30.23	29.81	30.01			
Thickness 3 (mm)	30.51	30.00	30.20	30.16			
Thickness 4 (mm)	30.20	30.20	30.81	29.58			
Thickness (mm)	30.52	30.19	30.40	29.98			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	275.41	272.43	278.02	267.13			
3	277.05	274.21	279.25	268.90			
5	277.50	274.65	279.60	269.38			
7	277.86	275.00	279.88	269.75			
9	278.17	275.29	280.10	270.07			
12	278.58	275.65	280.42	270.48			
16	279.01	276.09	280.80	270.96			
20	279.42	276.46	281.11	271.35			
25	279.87	276.88	281.48	271.79			
Saturated Mass (g)	290.13	287.01	292.76	282.67			
R^2 (Must be >0.98)	0.9998	0.9998	0.9997	0.9997			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	13.8	13.0	10.9	13.2			
Porosity (%)	12.9	12.9	13.0	13.8			

Sorptivity Results for Cement I for Curing in Air

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	I Solar						
Av. Sorptivity:	11.2	COV:	6.2				
Av. Porosity:	12.2	COV:	7.8				
Sample ID	54r11p3	54r12p18	54r21p18	54r22p18			
Diameter 1 (mm)	69	69.01	69.06	69.07			
Diameter 2 (mm)	69.15	68.98	69.1	69.12			
Average Diameter (mm)	69.08	69.00	68.00	69.00			
Thickness 1 (mm)	29.98	31.04	29.61	30.28			
Thickness 2 (mm)	29.93	31.21	29.30	30.30			
Thickness 3 (mm)	29.95	31.26	29.49	30.85			
Thickness 4 (mm)	29.58	31.15	30.10	30.83			
Thickness (mm)	29.86	30.00	30.00	30.00			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	269.25	290.95	266.60	285.79			
3	270.49	292.24	267.99	287.15			
5	270.81	292.57	268.33	287.52			
7	271.06	292.84	268.61	287.79			
9	271.26	293.07	268.85	288.03			
12	271.59	293.35	269.15	288.34			
16	271.95	293.69	269.51	288.68			
20	272.27	293.99	269.81	288.99			
25	272.64	294.32	270.15	289.31			
Saturated Mass (g)	283.77	303.71	280.81	298.54			
R^2 (Must be >0.98)	0.9992	0.9992	0.9999	0.9999			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	10.5	11.6	10.8	12.0			
Porosity (%)	13.0	11.4	13.0	11.4			

Sorptivity Results for Cement I for Curing in Solar Chamber

University of Cape Town and University of Witswatersrand							
Departments of Civil Engineering							
Sorptivity Test Analysis							
Sample ID:	I Water						
Av. Sorptivity:	12.6	COV:	7.4				
Av. Porosity:	12.5	COV:	8.2				
Sample ID	54w11p17	54w12p16	54w21p16	54w22p16			
Diameter 1 (mm)	69.32	69.15	69.2	69.28			
Diameter 2 (mm)	69.28	69.26	69.18	69.15			
Average Diameter (mm)	69.30	69.21	69.19	69.22			
Thickness 1 (mm)	28.47	29.54	29.91	29.17			
Thickness 2 (mm)	28.02	29.70	29.60	29.44			
Thickness 3 (mm)	28.40	29.92	29.40	29.74			
Thickness 4 (mm)	28.34	29.29	29.40	29.79			
Thickness (mm)	28.31	29.61	29.58	29.54			
Time (min)	Mass (g)	Mass (g)	Mass (g)	Mass (g)			
0	265.44	263.52	269.53	271.95			
3	266.53	265.25	271.11	273.53			
5	266.84	265.69	271.54	273.93			
7	267.12	266.06	271.90	274.24			
9	267.34	266.38	272.20	274.50			
12	267.64	266.77	272.61	274.84			
16	268.01	267.24	273.07	275.21			
20	268.28	267.65	273.45	275.52			
25	268.64	268.07	273.87	275.82			
Saturated Mass (g)	277.46	278.76	283.67	285.45			
R^2 (Must be >0.98)	0.9998	0.9998	0.9998	0.9998			
Range	3-25 min	3-25 min	3-25 min	3-25 min			
Sorptivity (mm/hr$^{0.5}$)	11.8	13.0	13.8	11.9			
Porosity (%)	11.3	13.7	12.7	12.1			

Sorptivity Results for Cement I for Curing in Water

Appendix 4.3: Water Absorption Results of Pycnometers

Cement:	CEM IV 32.5R			
Specimen no:	A2-0	CEM: FA = 100%:0%	w:cm= 0.35	
Cement (g)	Fly Ash (g)	Sand (g)	Water (g)	
500.0	0.0	500.0	175.0	
Time:	0.6			
	Mass Specimen A (g):	Mass Specimen B (g):		
	455.5	451.0		
	A Actual Reading	B Actual Reading		
0day initial	0.5	0.0		
3day actual	6.8	6.1		
7 day actual	1.6	7.0	Anew level on day 3 at 3pm refill=	
28 day actual	3.8	8.4		
Water Absorbed over Time				
	A	B	Average	
0D	0.0	0.0	0.0	
3D	1.4	1.4	1.4	
7D	1.6	1.6	1.6	
28D	2.3	1.9	2.1	
Relative to 28 Days				
	A	B	AVG	A2-0
0D	0.00	0.00	0.00	0.0
3D	0.60	0.73	0.66	66.3
7D	0.70	0.83	0.76	76.4
28D	1.00	1.00	1.00	100.0

Pycnometer Water Absorption Results A2-0

Cement:	CEM IV 32.5R	A2-15			
CEM: FA = 100%:15%	w:cm= 0.35				
Cement (g)	Fly Ash (g)	Sand (g)	Water (g)		
425.0	75.0	500.0	175.0		
	Mass Specimen A (g):	Mass Specimen B (g):			
	450.6	448.2			
	A Actual Reading	B Actual Reading			
0day initial	5.8	0.2			
3day actual	11.0	5.6			
7 day actual	11.8	6.3			
28 day actual	13.8	7.7			
Water Absorbed over Time					
	A	B	A2-15		
0D	0.00	0.00	0.00		
3D	1.15	1.20	1.20		
7D	1.33	1.36	1.30		
28D	1.78	1.67	1.72		
Absorption Relative to 28 Days					
	A	B	Average		A2-15
0D	0.00	0.00	0.00		0.0
3D	0.65	0.72	0.69		68.5
7D	0.75	0.81	0.78		78.2
28D	1.00	1.00	1.00		100.0

Pycnometer Water Absorption Results A2-15

Cement:	CEM IV 32.5R		
Specimen no:	A2-30	CEM: FA = 100%;30%	w:cm= 0.35
Cement (g)	Fly Ash (g)	Sand (g)	Water (g)
350.00	150.00	500.00	175.00
	Mass Specimen A (g):	Mass Specimen B (g):	
	449.68	449.61	
	21A Actual Reading	21B Actual Reading	
0day initial	2.20	3.80	
3day actual	7.60	9.20	
7 day actual	8.00		
28 day actual	10.20		
Water Absorbed over Time			
	21A	21B	1.30
0D	0.00	0.00	0.00
3D	1.20	1.20	1.20
7D	1.29	sample leaked - results discarded	1.29
28D	1.78		1.78
Absorption Relative to 28 Days			
	A	B	A2-30
0D	0.00	sample leaked - results discarded	0.00
3D	0.68		67.50
7D	0.73		72.50
28D	1.00		100.00

Pycnometer Water Absorption Results A2-30

Cement:	CEM IV 32.5R			
Specimen no:	D1-0	CEM: FA = 100%:0%	w:cm= 0.35	
Cement (g)	Fly Ash (g)	Sand (g)	Water (g)	
500.0	0.0	500.0	175.0	
	Mass Specimen A (g):	Mass Specimen B (g):		
	449.3	450.7		
	21A Actual Reading	21B Actual Reading		
0day initial	1.4	2.2		
3day actual	7.3	8.2		
7 day actual	8.6	9.2		
28 day actual	10.0	10.6		
Water Absorbed over Time				
	A	B	2.1	
0D	0.0	0.0	0.0	
3D	1.3	1.3	1.3	
7D	1.6	1.6	1.6	
28D	1.9	1.9	1.9	
Absorption Relative to 28 Days				
	A	B	Average	D1-0
0D	0.00	0.00	0.00	0.0
3D	0.69	0.71	0.70	68.6
7D	0.84	0.83	0.84	83.7
28D	1.00	1.00	1.00	100.0

Pycnometer Water Absorption Results D1-0

Cement:	CEM IV 32.5R			
Specimen no:	D1-15	CEM: FA = 100%:15%	w:cm= 0.35	
Cement (g)	Fly Ash (g)	1.0	Water (g)	
425.0	75.0	500.0	175.0	
	Mass Specimen A (g):	Mass Specimen B (g):		
	450.0	451.6		
	A Actual Reading	B Actual Reading		
0day initial	4.4	0.8		
3day actual	10.0	7.0		
7 day actual	11.0	8.0		
28 day actual	12.6	9.5		
Water Absorbed over Time				
	A	B	2.2	
0D	0.0	0.0	0.0	
3D	1.2	1.4	1.3	
7D	1.5	1.6	1.5	
28D	1.8	1.9	1.9	
Absorption Relative to 28 Days				
	A	B	Average	D1-15
0D	0.0	0.0	0.0	0.0
3D	0.7	0.7	0.7	69.8
7D	0.8	0.8	0.8	81.6
28D	1.0	1.0	1.0	100.0

Pycnometer Water Absorption Results D1-15

Cement:	CEM IV 32.5R			
Specimen no:	D1-30	CEM: FA = 100%:30%	w:cm= 0.35	
Cement (g)	Fly Ash (g)	Sand (g)	Water (g)	
350.0	150.0	500.0	175.0	
	Mass Specimen A (g):	Mass Specimen B (g):		
	451.8	451.5		
	A Actual Reading	B Actual Reading		
0day initial	2.4	0.5		
3day actual	7.8	7.4		
7 day actual	8.6	8.4		
28 day actual	10.6	9.4		
Water Absorbed over Time				
	A	B	2.3	
0D	0.0	0.0	0.0	
3D	1.2	1.5	1.4	
7D	1.4	1.7	1.6	
28D	1.8	2.0	1.9	
Absorption Relative to 28 Days				
	A	B	A2	D1-30
0D	0.0	0.0	0.0	0.0
3D	0.7	0.8	0.7	71.7
7D	0.8	0.9	0.8	82.2
28D	1.0	1.0	1.0	100.0

Pycnometer Water Absorption Results D1-30

Cement:	CEM IV 32.5R		
Specimen no:	I-0	CEM: FA = 100%:0%	w:cm= 0.35
Cement (g)	Fly Ash (g)	Sand (g)	Water (g)
500.0	0.0	500.0	175.0
	Mass Specimen A (g):	Mass Specimen B (g):	
	450.0	451.8	
	A Actual Reading	B Actual Reading	
0day initial	0.5	0.1	
3day actual	8.0	6.6	
7 day actual	Sample Leaked-Discard	7.1	
28 day actual		7.7	
Water Absorbed over Time			
	A	B	Average
0D	0.0	0.0	0.0
3D	1.7	1.4	1.6
7D		1.5	1.5
28D		1.7	1.7
Absorption Relative to 28 Days			
		B	I-0
0D		0.0	0.0
3D		0.9	85.5
7D		0.9	92.1
28D		1.0	100.0

Pycnometer Water Absorption Results I-0

Cement:	CEM IV 32.5R		
Specimen no:	I-15	CEM: FA = 100%:15%	w:cm= 0.35
Cement (g)	Fly Ash (g)	Sand (g)	Water (g)
425.0	75.0	500.0	175.0
	Mass Specimen A (g):	Mass Specimen B (g):	
	450.0	450.0	
	A Actual Reading	B Actual Reading	
0day initial	0.8	0.4	
3day actual	8.6	7.8	
7 day actual	9.4	Sample leaked-discard	
28 day actual	10.6		
Water Absorbed over Time			
	A	B	Average
0D	0.00	0.00	0.00
3D	1.73	1.64	1.69
7D	1.91		1.91
28D	2.18		2.18
Absorption Relative to 28 Days			
A			I-15
0.00			0.0
0.80			79.6
0.88			87.8
1.00			100.0

Pycnometer Water Absorption Results I-15

Cement:	CEM IV 32.5R			
Specimen no:	I-30	CEM: FA = 100%30%	w:cm= 0.35	
Cement (g)	Fly Ash (g)	Sand (g)	Water (g)	
350.0	150.0	500.0	175.0	
	Mass Specimen A (g):	Mass Specimen B (g):		
	450.4	450.1		
Water Absorbed over Time				
	A Actual Reading	B Actual Reading		
0day initial	0.2	14.0		
3day actual	6.5	19.8		
7 day actual	7.3	20.4		
28 day actual	9.3	21.8		
Absorption Relative to 28 Days				
	A	B	Average	
0D	0.0	0.0	0.0	
3D	1.4	1.3	1.3	
7D	1.6	1.4	1.5	
28D	2.0	1.7	1.9	
A	B	Average		I-30
0.00	0.00	0.00		0.00
0.69	0.74	0.72		71.79
0.78	0.82	0.80		80.04
1.00	1.00	1.00		100.00

Pycnometer Water Absorption Results I-30

Appendix 4.4: X-Ray Fluorescence Results of Various Fly Ash Specimens

Appendix 4.4.1: X-Ray Fluorescence Results for Mixes A2

Cement	A2	
Description	CEM IV/B-V 32,5R	
Fly Ash	0%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	43.93	40.46
Al2O3	14.45	13.59
Fe2O3	8.03	7.39
CaO	24.35	22.72
MgO	3.05	2.81
K2O	0.72	0.66
Na2O	1.97	1.77
TiO2	0.86	0.80
Mn2O3	0.15	0.14
P2O5	0.21	0.20
SrO	0.04	0.04
SO3	0.90	0.87
LOI at 950	2.21	9.37
Sum	100.86	100.81

XRF Results for Cement A2-0% Fly Ash Before and After Hydration

Cement	A2	
Description	CEM IV/B-V 32,5R	
Fly Ash	15%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	45.58	41.84
Al2O3	15.68	14.76
Fe2O3	8.12	7.19
CaO	21.40	20.95
MgO	3.05	2.67
K2O	0.75	0.66
Na2O	1.99	1.69
TiO2	0.92	0.85
Mn2O3	0.15	0.13
P2O5	0.22	0.22
SrO	0.04	0.04
SO3	0.78	0.73
LOI at 950	2.00	8.70
Sum	100.67	100.44

XRF Results for Cement A2-15% Fly Ash Before and After Hydration

Cement	A2	
Description	CEM IV/B-V 32,5R	
Fly Ash	30%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	46.893	45.319
Al2O3	17.018	16.077
Fe2O3	8.032	7.789
CaO	19.001	16.972
MgO	2.968	2.868
K2O	0.784	0.783
Na2O	1.949	1.973
TiO2	0.964	0.908
Mn2O3	0.139	0.135
P2O5	0.228	0.208
SrO	0.047	0.044
SO3	0.704	0.586
LOI at 950	1.8	7.14
Sum	100.527	100.802

XRF Results for Cement A2-30% Fly Ash Before and After Hydration

Appendix 4.4.2: X-Ray Fluorescence Results for Mixes D1

Cement	D1	
Description	CEM II/A-M (V-L) 42,5N	
Fly Ash	0%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	42.243	35.706
Al2O3	11.891	10.399
Fe2O3	8.495	7.084
CaO	27.585	29.958
MgO	3.325	2.784
K2O	0.705	0.572
Na2O	2.192	1.64
TiO2	0.774	0.689
Mn2O3	0.172	0.159
P2O5	0.177	0.165
SrO	0.032	0.031
SO3	0.857	1.013
LOI at 950	2.58	10.28
Sum	101.028	100.48

XRF Results for Cement D1-0% Fly Ash Before and After Hydration

Cement	D1	
Description	CEM II/A-M (V-L) 42,5N	
Fly Ash	15%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	42.898	38.402
Al2O3	13.372	12.334
Fe2O3	8.096	7.224
CaO	25.845	25.649
MgO	3.178	2.819
K2O	0.707	0.627
Na2O	1.976	1.774
TiO2	0.831	0.763
Mn2O3	0.163	0.15
P2O5	0.184	0.188
SrO	0.037	0.035
SO3	0.835	0.88
LOI at 950	2.32	9.79
Sum	100.442	100.635

XRF Results for Cement D1-15% Fly Ash Before and After Hydration

Cement	D1	
Description	CEM II/A-M (V-L) 42,5N	
Fly Ash	30%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	44.323	41.014
Al2O3	14.995	14.183
Fe2O3	8.05	7.321
CaO	22.834	22.393
MgO	3.072	2.832
K2O	0.74	0.653
Na2O	1.985	1.786
TiO2	0.886	0.836
Mn2O3	0.155	0.146
P2O5	0.2	0.208
SrO	0.041	0.04
SO3	0.751	0.78
LOI at 950	2.12	8.86
Sum	100.152	101.052

XRF Results for Cement D1-30% Fly Ash Before and After Hydration

Appendix 4.4.3: X-Ray Fluorescence Results for Mixes I

Cement	I	
Description	CEM II/A-V 52,5N	
Fly Ash	0%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	39.083	35.006
Al2O3	10.695	9.618
Fe2O3	8.037	7.223
CaO	32.75	30.846
MgO	3.134	2.861
K2O	0.637	0.556
Na2O	1.992	1.766
TiO2	0.733	0.669
Mn2O3	0.174	0.162
P2O5	0.178	0.177
SrO	0.033	0.03
SO3	1.446	1.39
LOI at 950	2.12	10.01
Sum	101.012	100.314

XRF Results for Cement I-0% Fly Ash Before and After Hydration

Cement	I	
Description	CEM II/A-V 52,5N	
Fly Ash	15%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	43.153	38.768
Al2O3	14.504	12.145
Fe2O3	7.827	7.37
CaO	25.41	25.465
MgO	2.976	2.836
K2O	0.711	0.634
Na2O	1.903	1.845
TiO2	0.878	0.761
Mn2O3	0.156	0.15
P2O5	0.209	0.189
SrO	0.042	0.036
SO3	1.111	1.112
LOI at 950	1.94	9.02
Sum	100.82	100.331

XRF Results for Cement I-15% Fly Ash Before and After Hydration

Cement	I	
Description	CEM II/A-V 52,5N	
Fly Ash	30%	
	Oxides Before Hydration - Day 0	Oxides After Hydration - Day 28
SiO2	43.773	40.795
Al2O3	14.575	13.553
Fe2O3	7.97	7.436
CaO	24.837	23.158
MgO	3.036	2.804
K2O	0.703	0.656
Na2O	1.949	1.82
TiO2	0.876	0.814
Mn2O3	0.155	0.145
P2O5	0.211	0.2
SrO	0.043	0.041
SO3	1.058	0.999
LOI at 950	1.81	8.64
Sum	100.996	101.061

XRF Results for Cement I-30% Fly Ash Before and After Hydration