The Use of Ternary Blended Binders in High-Consistence Concrete

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By

Mir Ali Shams

Department of Civil, Environmental and Geomatic Engineering
University College London

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Declaration

I, Mir Ali Shams, confirm that the work presented in this thesis is the result of my own investigations. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Mir Ali Shams

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Abstract

This study has investigated the feasibility and advantages of using ternary blended binders containing limestone powder (LP), i.e. Portland-limestone cement (PLC), with fly ash (FA) or ground granulated blastfurnace slag (GGBS) in three types of high-consistence concrete i.e. self-compacting concrete (SCC), flowing concrete (FC) and underwater concrete (UWC), concentrating on the hardened mechanical and durability properties.

Initially, mix design methods, tests, target fresh properties and constituent materials were selected for each concrete type. In the first stage of the study SCC mixes were formulated with binary and ternary binder blends with up to 80% cement replacement (by volume). The hardened properties of these, i.e. compressive and tensile strength, sorptivity and rapid chloride penetration resistance, were measured and the relationships between these investigated. Optimum replacement levels of GGBS and FA were estimated (40 and 20% respectively), and were used in the subsequent stages of the study on FC and UWC.

The main outcomes were:

- It is feasible to produce high-consistence concrete using ternary blended binders with LP and GGBS or FA.
- It is possible to achieve similar or higher long-term compressive strengths with ternary binder mixes than with binary binder mixes for concrete with low water/cement ratio (<0.4).
- A good relationship was obtained between the sorptivity results and the compressive strength which was independent of the concrete type, age and powder composition.
- No relationship between the rapid chloride penetration test results and the compressive strength was obtained; the results had a high degree of scatter.

There were reductions in the total embodied carbon contents of the concrete mixes with the incorporation of additions.

There is scope for further investigating the synergistic effect between limestone powder and ggbs and fly ash to further reduce the Portland cement content leading to greater potential economic and environmental advantages.

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Chapter 1 Introduction

This chapter begins by giving a brief introduction to high-consistence concrete (HCC) and its application, then moves on to describe the research background and finally goes on to mention the aims and scope of this research and the structure of the thesis to follow.

1.1 Introduction to high-consistence concrete

High-consistence concrete (HCC) is defined as a concrete of a flowing consistency with a slump value in excess of 200mm, which can be placed and compacted with little or no effort whilst being cohesive enough to be handled without segregation and bleeding (Domone & Illston, 2010; Neville, 2011). HCC has been increasingly used in recent years; examples include flowing concrete, underwater concrete, concrete for piled foundations and, most recently, self-compacting concrete. Such concrete requires high quantities of Portland cement or similar powder together with admixtures such as superplasticisers to achieve a satisfactory combination of fluidity and stability.

Compared to normal-consistence concrete, HCC does offer certain advantages such as (The Concrete Society & BRE, 2005; Neville, 2011):

- Ability to place concrete, with minimal or no vibration, in areas with congested reinforcement and/or poor access
- Noise reduction and improved safety on site
- Time saving in concrete placement

However there are also disadvantages such as (The Concrete Society & BRE, 2005; Neville, 2011):

- Higher cost due to the high powder content and the need for chemical admixtures of HCC
- High powder content leads to increased heat of hydration hence increased risk of thermal cracking
- Increased sensitivity hence greater quality control measures are required to control mixes
- Increased formwork pressure hence increased formwork costs

The increased use of HCC has been concurrent with the drive towards greater sustainability within the construction industry with concrete playing a major role in this.

1.2 Research background

This section therefore begins by giving a brief overview of the move towards sustainability within the construction sector in general and its importance. It later focuses on the cement and concrete industry, these being two of the major sub-industries, and describes the methods and techniques they use in order to achieve greater sustainability within their industry.

1.2.1 Sustainability in the construction industry

Engineering has been the reason for various developments in the world in the past centuries e.g. infrastructure, living standards and the economy, however these developments have detrimental effects on our planet such as damage to the surrounding environment and high rate of consumption earth’s natural resources. Also owing to the modernisation of human lifestyle over time, it has become clear that the current new/modern lifestyle cannot be sustained for much longer. This reinforces the need for future developments to be more sustainable; engineers need to recognise the need to protect and improve the environment and use resources in a way not to disadvantage future generations.

Chapter 1 Introduction

The construction industry has a very important role to play in delivering sustainable development for many economic, social and environmental reasons (UK Contractors Group, 2009; Harris, 2012; Department for Food Environment and Rural Affairs, 2008; Office for National Statistics, 2013):

Economic importance

- Within the UK, the construction industry, consisting of over 300,000 firms, has an annual value of about £120 billion (2012 figure) or in other words approximately 10 per cent of the country's GDP
- It employs over 2 million people

Social importance

- Almost 90 per cent of our lives are spent in buildings, whether at work, home, school or leisure
- In commercial buildings, our productivity is greatly dependent on the built environment

Environmental importance

- The construction industry consumes about 420 million tonnes of raw materials annually (2008 figures) which is about one quarter of all raw materials used in the country
- Construction and demolition activities produce around 120 million tonnes of waste every year, of which only 50% is recycled.

Achieving sustainability within the construction industry is not easy due to it being made up of many different sub-industries. Hence the best way forward would be for every sub-industry to contribute, within their capabilities, towards sustainable development and together they can move towards achieving a greater overall sustainability within the whole industry.

1.2.2 Cement and concrete industry

1.2.2.1 Cement industry

Cement is the key component material in concrete which is the second most consumed substance in the world after water (Mineral Product Association (MPA), 2012). The industry contributes nearly a billion pounds annually to the UK economy, operating 12 plants, producing around 10 million tonnes of Portland cement (CEM I) annually (MPA, 2011). The worldwide cement production in 2007 was 2.77 billion tonnes with Europe accounting for about 10% of the total at 270 million tonnes (The European Cement Association (CEMBUREAU), 2009). With the construction industry growing on average at 3 – 5% per annum, the demand for cement has been steadily rising at about 1% per annum. This rising demand is mirrored by the significant developments within the UK cement industry i.e. more compact and more efficient, over the past decades; in 1966, with 121 kilns, the average production per kiln was about 146,000 tonnes whereas in 2006, with only 19 kilns, the average production per kiln stood at about 800,000 tonnes (Clear, 2006; MPA, 2011).

Cement production has several quite serious environmental hazards associated with it such as (MPA, 2011):

- Release of dust, oxides of nitrogen (NO_x), sulphur dioxide (SO_2) and carbon dioxide (CO_2) in to the atmosphere
- Use of resources (fossil fuels and primary raw materials)

Over the past few decades cement manufacturers have been under increasing pressure to reduce the extent of their environmental hazards in particular harmful emissions in to the atmosphere. The UK cement industry has, over the past 10 years, been constantly working towards reducing its harmful emissions and according to a recent report published by the MPA (2011), the 2010 figures indicate that, relative to the 1998 baseline, they have been successful in reducing emissions of dust, NO_x and SO_2 by 83%, 59% and 87% respectively along with a reduction of 22% in the CO_2 emissions for the reasons explained below; albeit the current CO_2 emissions are still high.

- Increased use of alternative (waste-derived) fuels
- Reduction in the clinker content of the cement
- Increased efficiency of the cement making process

In terms of the increase in use of alternative fuels, in 2010 the industry was able to replace 38.1% of the fossil fuels with waste derived fuels which already surpasses their 2050 target of 30% replacement. In order to reach this high level, a wide variety of wastes have been utilised including tyres, recycled liquid fuel, processed sewage pellets, biomass fuels, paper and plastics, waste oils and wood (MPA, 2011). The use of such fuels leads to less waste being sent to landfill or incinerated, preserves natural fossil fuel reserves and reduces the overall greenhouse gas emissions (Figure 1-1). Waste-derived fuels are less carbon intensive than traditional fuels such as coal and can result in a 20 to 25% reduction in ‘gross’ emissions. In addition the use of these fuels in cement kilns has indirect savings as this avoids CO_2 emissions from waste incineration and also any mineral content in these fuels is incorporated into the clinker matrix hence no residual ash is produced; for instance tyres have iron-oxide present in them which contributes as a raw material for the cement making process, therefore a zero ‘net’ emission factor can be used for all waste-derived fuels (The Cement Sustainability Initiative, 2009). However it must be noted that in cement manufacture only 35% of the CO_2 emissions is due to fuels burned in the kiln (“fuel CO_2”) and the remaining 65% is due to the decomposition of limestone during the ‘calcination’ process (“process CO_2”) (Mineral Product Association (MPA), 2012). Hence even if the industry is able to replace all of the fossil fuels with waste-derived fuels, the total ‘net’ emissions would only be reduced by 35%.

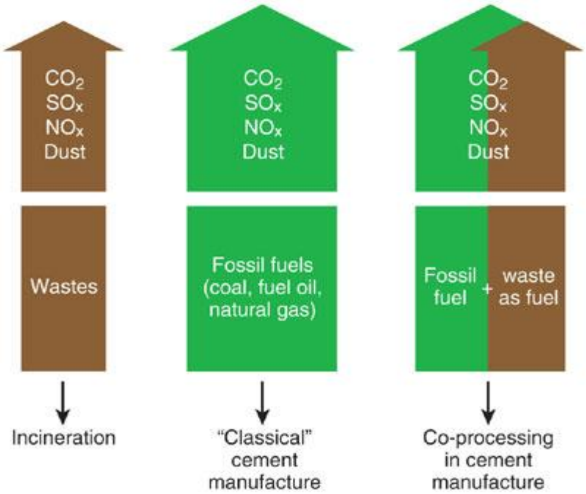


Figure 1-1 Greenhouse gas emission with use of waste-derived fuels in cement manufacture (Portland Cement Association, 2013)

According to the MPA (2012), the use of alternative fuels and the improvement of the cement making process can only be a short term solution. In the medium term (till 2030), the industry plans to continue reducing CO_2 emissions through the increase in use of waste-derived fuels but also to increase the production of factory-made composite cements (CEM II) i.e. lower clinker cements with addition materials such as fly ash (FA) (a by-product of the coal burning power stations), ground granulated blast furnace slag (GGBS) (a by-product of the manufacture of iron) and limestone powder (LP). Looking ahead to 2050, the industry is considering Carbon Capture and Storage (CCS) as a long term solution for dealing with the "process CO_2", however this would require a great financial input and as well a greater technical understanding is needed in order to be able to efficiently and cost-effectively introduce such a technique (Schneider et al., 2011).

One method of assessing materials based on their environmental impacts is to look at the 'embodied carbon' content of the material. This is estimated by summing all the CO_2 emissions over the life-cycle of the material (Hammond & Jones, 2008). At present, in the UK, the embodied CO_2 for the production of pure Portland cement (PC) (CEM I, ground clinker) is about 913 kg/tonne and globally the CO_2 released by the cement industry accounts for 5% of the total man-made greenhouse gas emissions (Mineral Product Association (MPA), 2012). The production of composite cements could lead to a substantial reduction in embodied CO_2 as the value for the waste-derived materials i.e. FA, GGBS and LP are much lower standing at 4, 67 and 75 kg/tonne respectively (MPA, 2010). According to the 2007 data, the embodied CO_2 for LP was reported as being 32 kg/tonne, less than half the current reported value (which was obtained from only one UK supplier). However the percentage replacement of these additions is usually limited by the performance of the resultant concrete and not by process. According to the latest figures, 27.8% of the total cementitious materials used are waste-derived additions (Sustainable Concrete, 2011). Another method could be improving the clinker reactivity, hence then cement with less clinker content having the same performance would be achievable. This could be achieved by increasing the content of Alite (C_3S) or by grinding the clinker to a finer size however high Alite content could result in long-term durability issues and grinding consumes energy which might in turn offset its benefits.

Recent research has been looking at developing ‘novel’ cements which are not based on traditional processes and are generally non-Portland. These cements tend to have less embodied energy and emit less carbon dioxide in to the atmosphere; also the processes ideally would use waste-derived fuels and raw materials. However there is still vast amount of research to be done in order to prove the feasibility of these ‘novel’ cements and to be able to incorporate them in the industry on a large scale. Some of these ‘novel’ cements are (Juenger et al., 2011; Schneider et al., 2011):

- Alkali-activated cements
- Geopolymer cements
- CSA-belite cements
- Magnesium oxide-based cements
- ‘Ecocements’ based on municipal solid waste incinerator ash (MSWIA)
- C-Fix cement (thermoplastic binder which is a by-product from the oil refinery industry)

However one of the key challenges for these types of cement to be successful as new general-purpose cement on a wide-scale, i.e. globally, is that certain criteria must be fulfilled such as:

- It must be capable of being manufactured in high volumes
- It should be relatively inexpensive
- The raw materials required for the production should be readily available around the world
- It must have an acceptable and proven long-term performance

Hence at the present time, finding ways of further reducing the clinker content of cement, by looking into multi-blend CEM II composite cements using various different additions, seems to be an attractive route provided acceptable performance levels are maintained.

1.2.2.2 Concrete industry

Concrete is the most widely used construction material in the world, from the building we work in or live in to roads, bridges and tunnels that we use for our transport. As PC is the vital material in concrete and also the most expensive, when estimating the carbon footprint of concrete production we encounter the high level of embodied carbon of cement production leading to a conclusion that concrete production is environmentally unfriendly. In addition to the high carbon footprint of concrete, there are other wider sustainability issues which are worth mentioning such as:

- *Whole-life effect*: Looking at environmental, social and economic impacts, of a given product throughout its lifespan.
- *Durability*: This basically looks at effect of the durability of the concrete product on its whole-life effect. For example, producing a more durable concrete could have a higher initial cost but might compensate for that over its lifetime by the reduction in required maintenance.

- *Thermal efficiency*: Using the thermal mass of the concrete (its ability to absorb, store and release energy) which could help regulate the temperatures in buildings. This could result in reduction in energy use within the building.
- *End-of-life recycling*: Considering methods of being able to recycle and reuse concrete structures which have reached the end of their life. This is done by producing recycled concrete aggregates (RCA) from these structures and using them as a substitute for natural aggregates when producing concrete.

Focusing on the high carbon footprint of concrete production, reducing the amount of PC used in concrete would benefit the environment and also lead to cost savings. However, in addition to PC (section 1.2.2.1), other materials used in concrete such as aggregates and admixtures (embodied CO_2 of 4 and 325 kg CO_2/tonne respectively (Sustainable Concrete, 2012)) also contribute to the total embodied CO_2 due to their manufacturing process hence must not be excluded. In addition to the embodied carbon of the raw materials, the production of concrete itself, i.e. batching, mixing and transporting, also contributes to the total embodied CO_2 (which on average currently stands at around 83 kg CO_2/tonne of concrete (Sustainable Concrete (2012)), but fortunately none of the above have a value as high as PC. It must be noted that even though the embodied CO_2 of the admixtures is relatively higher than other component materials of concrete (apart from PC), they are used in very small dosages ranging from 0.1 to 2% by weight of binder depending on the specific admixture hence it has a small effect on the total embodied carbon of concrete. The combined effect of the reduction in the embodied CO_2 of cement production and the concrete industry using less cement results in a substantial reduction in CO_2 emissions.

In addition to the great strides made by concrete producers and users in reducing the carbon foot print of concrete, over a similar period, advances in admixture technology has enabled concrete with enhanced workability i.e. HCC, to be developed and increasingly used. Within the EU (excluding Norway and Switzerland) the percentage production of these types of concrete (as a percentage of the total production) has increased from 12% in 2003 to about 42% in 2011 and similarly within the UK, the percentage production of these types of concrete has increased from 1% in 2002 to about 19% in 2011 (European Ready Mixed Concrete Organisation (ERMCO), 2012). The advances in admixture technology were due to the challenges created by the construction industry through designing concrete structures with greater complexity having densely arranged reinforcement bars needing a concrete that can flow through the bars and compact with minimal vibration. After utilising the initial advances in the technology, further complexities of design have given admixture producers ever greater challenges. For example during the construction of Burj Khalifa in the United Arab Emirates, due to the hot and humid weather, one of the main challenges was to pump concrete vertically for the construction of the core wall whilst maintaining acceptable performance of the concrete. With the use of various admixtures not only were they able to pump HCC mixes but they managed to break the record for the highest vertical pump setting it at 601m (Burj Khalifa, 2012). With the continuous advancements in the admixture technology leading to an increase in usage of HCC, there is the potential for using greater quantities of various additions as part of the binder for both technical (e.g. lower heat of hydration, improved durability) and environmental (e.g. reduce waste to landfill, reduced cement content) advantages.

1.3 Aims and scope of research

This research focuses on extending the use of ternary binders of Portland cement and additions in three different high-consistence concrete i.e. self-compacting concrete (SCC), flowing concrete (FC) and underwater concrete (UWC), whilst maintaining acceptable performance levels. The aim is therefore to increase the quantity of addition combinations that can be successfully used in HCC. The additions considered for this research are fly ash, ground granulated blastfurnace slag and limestone powder.

This research comprised three main areas:

1. A review of current practice including mix design and production procedures for each of the high-consistence concrete types, and discussions with the producers and users of each of the above materials and the resulting concrete.
2. Analysis of availability and potential advantages of each material, including environmental considerations.
3. A test programme of fresh, early age and hardened properties of concrete.
    a. Fresh properties: Rheology and consistence tests;
    b. Early age properties: Strength gain and heat of hydration;
    c. Hardened properties: Strength, stiffness, durability.

The first stage involved reviewing the current practice and the various mix design procedures available and selecting an appropriate one to use for each type of concrete. In addition, it involved discussions with both the concrete and material suppliers and users to get suggestions and feedback on the research idea allowing the work to be tailored to the needs of the industry. This enabled the production of a reference control mix for each type of concrete with PC as the sole binder.

The objective of Stage 2 was to review the availability of each material, look at how they have been utilised in concrete in the past discussing the potential advantages they offer, including environmental considerations such as reduction in greenhouse gas emissions and reduced waste to landfill.

The aim of stage 3 was to develop and carry out a test programme for the various concrete mixes. Prior to starting the test programme, a reference control mix was produced for each concrete type whose fresh properties were within the set target range (set in stage 1). Mixes with binary and ternary blended binders were then produced with various replacement levels of additions i.e. GGBS, FA and LP, with their fresh properties being within the target range (further detail in Chapter 3). The hardened mechanical properties of these mixes were then investigated, and these included measurement of compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV), dynamic elastic modulus (E_d) in addition to two durability tests namely sorptivity and rapid chloride penetration (RCP) test.

1.4 Thesis structure

Chapter 2 begins by giving a brief introduction to three types of high-consistence concrete i.e. self-compacting concrete, flowing concrete and underwater concrete including advantages and disadvantages. It also looks at the test methods available for each concrete type. It then moves on to give a detailed review of GGBS, FA and LP as additions in binary blended binder concrete and also reviews the use of ternary blended binders with those powders. The chapter ends with a section summarising the discussions with industrial personnel regarding the research topic and formulation of a test programme.

Chapter 3 summarises conclusions from Chapter 2 (literature review) which are relevant to this research project, and hence defines the overall objectives and the testing programme.

Chapter 4 gives the mixing procedures and test methods used throughout the experimental works.

Chapter 5 describes and discusses all the constituent materials used in the project i.e. cement, fly ash, ggbs, limestone powder, aggregates and water, including their physical and chemical properties. It also describes the various admixtures used i.e. superplasticiser, viscosity modifying and anti-washout admixtures.

Chapter 6 explains the mix design method used for each of the three concrete types including the process of obtaining the reference control mix for each.

The obtained test results of binary and ternary blended binders for self-compacting concrete and flowing and underwater concrete are shown and discussed in Chapters 7 and 8 respectively. All concrete mixes within each type had similar target fresh properties and the hardened mechanical and durability properties were measured at various ages from 1 to 91 days.

In Chapter 9, for each concrete type, the entire set of results is combined and analysed and consequent relationships shown and discussed. In addition, comparisons are made between the results of the different concrete types and correlations discussed.

Conclusions for the whole project including suggestions for future work are given in Chapter 10.

Chapter 2 Literature Review

The increase in research and development in use of addition materials in concrete over the past two decades has led to a substantial amount of publications being produced in this area. Those considered most relevant to this study are reviewed and summarised in this chapter.

This chapter begins by giving a brief introduction to the three types of high-consistence concrete relevant to this study i.e. self-compacting concrete, flowing concrete and underwater concrete, followed by a discussion of test methods. This is followed by a detailed review of the use of ground granulated blastfurnace slag, fly ash and limestone powder as additions in concrete. A brief summary of discussions with industrial personnel regarding the research topic is also given.

2.1 High-consistence concrete

As mentioned in the previous chapter (section 1.1) the core requirement for high-consistence concrete is that it should have a slump value greater than 200mm. Also, again as mentioned previously, there are different types of high-consistence concrete, each of which has its own additional requirements. In this section, three different types of high-consistence concrete i.e. flowing concrete, underwater concrete and self-compacting concrete, are discussed.

2.1.1 Flowing concrete

The development of superplasticisers made it feasible to produce concrete having high-consistence with minimal bleeding and segregation. This came to be known as ‘flowing concrete’ with the term first appearing about 40 years ago (Domone & Illston, 2010). For a concrete to qualify as a flowing concrete (FC), the requirements are that it must have a slump value of about 200-240mm (high consistence) and little or no bleeding and segregation (good stability and cohesiveness). Although the concrete might be self-levelling, it does require some vibration to achieve full compaction, however the duration of vibration is almost half that required for a lower consistence mix (Neville & Brooks, 2010). Flowing concrete could be classified as the simplest type of high-consistence concrete.

2.1.2 Underwater concrete

Underwater concrete (UWC) refers to concrete that is placed underwater. Applications range from construction of foundations of harbours to deep-sea placing (Domone & Illston, 2010). This capability of the concrete to be placed underwater eliminates the need to isolate the concreting area from the surrounding water which saves both time and money. The placing of concrete can be done in two ways: the first is by simply dropping the concrete through the water in to the formwork that has been placed at the sea or river bed and the second, more controlled and preferred way, is by the tremie method in which the concrete is gravity-fed through a vertical pipe where the open-end of the pipe is buried in the fresh concrete already placed (Domone & Illston, 2010; Neville, 2011). Concrete placed underwater is inherently vulnerable to cement washout, segregation, laitance, cold joints and water entrapment; hence it is reasonable to say such concrete must possess some unique characteristics (Yao & Gerwick, 2004). The essential requirements are that the concrete must flow easily (slump range 200-250mm), retain enough cohesion against washout (washout resistance), be stable with minimal or no segregation and lastly it must possess reasonable self-compacting characteristics because it is impractical and sometimes impossible to compact concrete underwater using the conventional mechanical vibrators.

2.1.3 Self-compacting concrete

Self-compacting concrete (SCC) is defined as a concrete, which under its own weight, will flow into place and completely fill the formwork, while maintaining homogeneity even in the presence of congested reinforcement, and then consolidate without the need for vibration (The Concrete Society & BRE, 2005). It was developed in Japan in the late 1980s because, due to the increasing reinforcement volumes and lack of skilled construction workers, it was difficult to obtain full compaction resulting in poor quality concrete (Okamura & Ouchi, 1999).

SCC has three characteristic features which makes it different to other concrete types, these are filling ability, passing ability and segregation resistance (The Concrete Society & BRE, 2005). Filling ability refers to the deformability of SCC, i.e. the ability of SCC to change shape under its own weight in the fresh state. This can be divided in two parts, the first is the distance the concrete can flow (deformation capacity) and second is speed of flow (deformation velocity). Passing ability or no blocking tendency of SCC gives an indication of how well the concrete can flow through and around obstacles and narrow spaces such as congested reinforcement without blocking, which can be caused by aggregates bridging between the reinforcement bars. Lastly, segregation resistance refers to the requirement of the mix to remain homogeneous during and after transportation and placing.

The above are the key properties of SCC and are in a way inter-dependent in that a change in one property will normally result in the change in one or both of the other properties. For example, higher filling ability increases the risk of segregation whereas a low filling ability could lead to insufficient passing ability (blocking). For each of the properties there is an acceptable range within which the concrete would qualify as SCC, hence the different properties can be adjusted depending on the application.

All the above three qualify as high-consistence concrete however each of them has characteristics in the fresh state which are unique to that type of concrete. In order to achieve these unique characteristics, the mix proportioning recommendations are different for each type; this is further discussed in Chapter 6. Flowing concrete can be said to be the simplest of the three with requirement of high slump and good stability whereas SCC seems to be the most complex as it involves balancing the three key properties of filling ability, passing ability and segregation resistance of the mix to achieve an acceptable concrete. The hardened mechanical and durability properties of high-consistence concrete are assessed in the same way as that of normal-consistence concrete. However numerous test methods have been developed to assess the fresh properties of high-consistence concrete. These are discussed in the next section.

2.2 Fresh property tests

In this section, for each of the three concrete types, the test methods used for the assessment of their fresh properties is discussed with diagrams and dimensions of all tests given in Appendix 1.

2.2.1 Flowing concrete

As mentioned in 2.1.1, flowing concrete should have high consistence and good stability and cohesion. The tests used to assess the fresh properties of flowing concrete are described below.

2.2.1.1 Slump test

The slump test is oldest and most widely used test for assessing the workability of concrete. It was developed by Abram in 1918 and the test procedures are described in BS EN 12350-2 (2009). The test involves a frustum cone (Abrams cone), 300mm high, being filled with concrete and hand compacted in three successive layers. The cone is then lifted vertically, and the slump is measured as the downward movement of the concrete. This test was developed with the intention of assessing the workability of normal-consistence concrete, with slump values up to 180mm considered as true slump, as the concrete retains to some extent the overall shape of the cone. Testing high-consistence concrete mixes, such as flowing concrete, using this method results in a collapse slump, which is not ideal, however due to the increasing use of high-consistence mixes, many standards such as BS EN 206-1 (2000) now consider slump values of about 250mm as valid (Domone & Illston, 2010). The slump test is a single-point test as it only measure one value, and gives an assessment of the yield stress (force required to start flow) of the concrete however it gives no indication of the plastic viscosity (resistance to flow once flow has commenced) of the mix as it is measured on a stationary cone of concrete (shear rate assumed as zero). For high-consistence concrete mixes, the final diameter of the concrete is more sensitive to changes in the mix than the change in drop height of concrete; hence as an alternative, the mean flow diameter of the concrete can be measured (Domone & Illston, 2010).

2.2.1.2 Flow table test

As mentioned above, changes in the workability of high-consistence concrete seem to be more noticeable with the change in the flow diameter of the mix rather the change in drop height (slump); hence this test was developed to allow better differentiation between high-consistence mixes. The test is similar to the slump test but with a smaller cone of concrete, however some extra work is done on the concrete by lifting one edge of the board on which the test is being carried out to a specified height and dropping it a prescribed number of times. The final diameter of the concrete is then measured and recorded. The flow or spread values range from less than 340mm for low consistence concrete to above 500mm for high-consistence concrete. This test has become more widespread with the increase in use of high-consistence mixes, mainly due to its simplicity and ease of use both in the laboratory and on site. The result of this test can be correlated to slump, with higher slump mix having the higher flow. The test procedures are described in BS EN 12350-5 (2009).

No requirements have been set for the segregation resistance of flowing concrete mix apart from that it must have little or no segregation. No tests have been developed to assess the segregation resistance of flowing concrete but by visual inspection of the circumference of the concrete after the slump test an experienced operator can get a qualitative indication of the concrete’s stability.

2.2.2 Underwater concrete

The ideal underwater concrete mix should have high consistence, good stability and be resistant to washout. Similar to flowing concrete, the conventional slump test (2.2.1.1) and the flow table test (2.2.1.2) can be used to assess the consistence of the underwater concrete mix and similarly the segregation resistance can be assessed visually after the test. Tests for assessing the washout resistance of underwater concrete mixes are discussed below.

2.2.2.1 Stream test

This test was developed in Belgium (Davies, 1986); it can be used both in the laboratory and on site and gives a visual assessment of the degree of washout resistance of the concrete mix. Test is performed using a 2m long, 100-150mm diameter sloping guttering channel (15-20° to the horizontal). A sample of concrete is then placed about 300mm from the raised-end and water is poured down the guttering channel and over the concrete sample. The amount of washout is then determined visually which makes this test strongly operator sensitive when comparing different mixes. Other factors which also affect this test are the rate at which the water is being poured, as the faster the water is poured the greater the washout, and also it is important that the same volume of water is poured down the channel at the same point for every test. Any changes in these factors could affect the amount of washout (Sonebi et al., 1999).

2.2.2.2 Drop test

The only apparatus required for this test is a graduated cylinder filled with water. A small scoop-full of concrete (300-500g) is dropped through the water and the resultant turbidity of the water is visually assessed to give an indication of the degree of washout (Davies, 1986; Sogo & Haga, 1987). As with the stream test, this is also a qualitative test and is very much dependent on the experience of the operator in making an assessment. Sonebi et al. (1999) mentioned that the degree of turbidity can be quantitatively measured by using a spectrophotometer or similar equipment.

2.2.2.3 Plunge test

The plunge test is the only test out of the three washout tests that provides a quantitative result. It was standardised by the US Corps of Engineers in CRD C61 (1989). It is performed by plunging a basket, 130mm in diameter 120mm high, with 3mm perforations, full of concrete three times through 1.7m of still water in a cylindrical container. The washout is calculated as the percentage between the mass loss (washed out) of concrete and the mass of concrete before immersion. Work at the University of Paisley concluded that it was not possible to obtain accurate washout resistance using this test due to the fact that the aggregates in the mix could block the perforations around the basket preventing washout (Annett, 1987; Sonebi et al., 1999).

2.2.3 Self-compacting concrete

As mentioned in 2.1.3, a successful self-compacting concrete must have three distinct fresh properties: filling ability, passing ability and segregation resistance. Since the development of self-compacting concrete in Japan in the late 1980s, numerous tests methods of different forms have been introduced to evaluate these fresh characteristics of the mix as the existing standardised tests at that time were unsuitable for assessing these characteristics. A number of early tests were developed such the U-flow test, developed by the Taisei Group, and its modified version the L-box test. Both assess the filling and passing ability of SCC indicated by the height the concrete reaches after passing through an obstacle (a gate consisting of reinforcement bars) (Okamura & Ouchi, 2003). However these two tests only gave an indication of the filling and passing ability of the mix and no indication of the segregation resistance. Other tests were developed, such as the filling vessel or fill box test, aimed at assessing the filling and passing ability and the segregation of the SCC mix. In this test the concrete was poured into a box containing horizontal reinforcement bars, allowed to flow throw the mesh of bars, and the difference in the concrete height between the filling side and the opposite side is used to evaluate the SCC mix (Bartos et al., 2002). As mentioned in 2.1.3, the three key properties of SCC are interrelated, hence one single test, such as the fill box test, was able to evaluate the overall performance of the mix which is the compound effect of all three key properties but not the performance of the mix with respect to each of the properties individually. This makes it much more difficult to readjust a ‘bad’ SCC mix as there is no indication of which particular property needs further improvement e.g. poor filling ability or poor segregation resistance or blockage cause by poor passing ability. As a result, these early tests are now rarely used and instead, at present several tests are used in combination aiming to evaluate one of the three key properties of SCC. Five tests which are widely accepted and have recently been standardised in Europe are discussed further.

2.2.3.1 Filling ability tests

The filling ability of SCC, as mentioned, refers to its deformability and the two aspects that are evaluated are the distance and speed of flow. A different test is used to assess each aspect; these are the slump flow test and the V-funnel test respectively.

2.2.3.1.1 Slump flow test

The slump flow test (BS EN 12350-8, 2010) is in some ways similar to the slump test (2.2.1.1), the apparatus used is the same with the only difference being that in this case no compaction is involved. After the slump cone is lifted, the mean diameter of the final concrete flow (slump flow) is measured instead of the drop in height of the concrete (slump). This test is widely used to evaluate the deformation capacity (flow distance) of the concrete, provided no segregation occurs, the higher the slump flow, the greater the deformation capacity of the concrete. In addition, T500, the time taken for the concrete to reach 500mm diameter, can also be measured, which assesses the deformation rate of the concrete mix. The lower the deformation rate of the concrete, the longer time it takes to flow, hence the greater the T500 time.

Theoretically the concrete would cease to flow once driving force (shear stress) becomes equal to or less than the yield stress of the mix (force required to initiate flow). The slump flow of SCC showed good correlation with the yield stress of the mix and poor correlation with the plastic viscosity, indicating that the yield stress is the dominant factor governing the slump flow diameter (Testing-SCC, 2005). On the other hand, the T500 time showed good correlations with the plastic viscosity of the mix and poor correlation with yield stress indicating the T500 is more affected by plastic viscosity of the mix (resistance to flow once the flow has started) than the yield stress (Testing-SCC, 2005). The segregation resistance can be visually evaluated by observing the flowing process and the edges of the concrete spread as the uneven distribution of coarse aggregates or an occurrence of a halo of paste is considered to be an indication of segregation (Testing-SCC, 2005). Having said that it is important to note that this technique of evaluating segregation is only visual and nonexistence of segregation during the slump flow cannot be used as an assurance that the mix has good segregation resistance.

2.2.3.1.2 V-funnel test

In the V-funnel test (BS EN 12350-9, 2010), the time taken for the concrete mix to flow out of a V-shaped funnel, under its own weight, is measured. This test is used to evaluate the second of the two filling ability aspects, deformation velocity (speed of flow). This test is also affected by the passing ability and segregation resistance of the concrete mix, as a longer V-funnel time could be caused by higher inter-particle friction or blockage of flow respectively. The V-funnel time showed good correlation with the plastic viscosity of the mix and poor correlation with the yield stress of the mix, however the T500, measured as part of the slump flow test, showed better correlation with the plastic viscosity than the V-funnel time (Testing-SCC, 2005).

2.2.3.2 Passing ability tests

The passing ability of concrete refers to how well the concrete flows through narrow openings and around obstacles such as in areas of congested reinforcement. Among the various tests designed to measure the passing ability of SCC, two tests, the J-ring test and the L-box test, have been standardised and are commonly used, both simulating flow of concrete through reinforcement.

2.2.3.3.1 L-box test

The L-box (BS EN 12350-10, 2010) is made up of a vertical and a horizontal arm. In the test, concrete is allowed to flow from the vertical arm, through a vertical arrangement of reinforcement bars into the horizontal arm of the box. The test is completed once the concrete has ceased to flow, and then the passing ability of the concrete is assessed by measuring the height of the concrete in the vertical arm (H1) and the height of the concrete at the end of the horizontal arm (H2). The ratio of H2 to H1 (known as blocking ratio) is used as the quantitative assessment of the passing ability of the concrete. A blocking ratio of 1 would mean no blocking at all indicating that the SCC has perfect passing ability and on the other hand, a blocking ratio of 0 would mean complete blockage of flow indicating that the SCC has very poor or no passing ability. In Testing-SCC (2005), it has been recommended that three vertical reinforcement bars (equally spaced) should be used when assessing mix for a densely reinforced structure and two vertical bars should be used when assessing mix for a less densely reinforced structure. Visual assessment of segregation can also be performed, such as checking if the coarse aggregates are stuck between the reinforcement bars or unevenly distributed along the concrete in the horizontal arm, both of which indicate segregation tendency of the mix.

2.2.3.3.2 J-ring test

The J-ring test (BS EN 12350-12, 2010), similar to the L-box test, simulates flow of concrete through reinforcement assessing its passing ability. One difference between the two tests is that in the L-box test the flow of concrete was confined whereas in this case the flow is unconfined. The test apparatus is similar to that for the slump flow test (2.2.3.1.1) with the addition of a 300mm diameter ring of equally spaced reinforcement bars (12 or 16 vertical bars). The slump cone is placed in the centre of the reinforcement ring, filled with concrete and as the cone is lifted the concrete has to involuntary pass through and around the reinforcement bars as it moves across the plate. The test is completed once the concrete has stopped flowing. The passing ability of the concrete is then assessed using the average height difference (step height) between the concrete at the centre of the ring (highest point of concrete) and just outside the reinforcement bars. Lower step height would indicate better passing ability and vice versa. The average flow diameter of the concrete is also measured. Similar to the slump flow test, the segregation tendency of the concrete mix can be visually assessed by observing at the outer circumference of the concrete spread where the presence of a halo or uneven distribution of coarse aggregates could be indicative of segregation.

2.2.3.3 Segregation resistance tests

The last of the three key properties of SCC, segregation resistance, refers to the tendency of the mix to remain homogeneous during processes of transportation and placing and after placement. Segregation of the concrete can occur either during transportation and placement (dynamic segregation) or after placement (static segregation). As mentioned, with the slump flow test and the J-ring test, a crude method of assessing segregation is by visually assessing the periphery of the concrete flow for signs of segregation. As an attempt to standardise the visual assessment method and allow simple comparison between mixes, the visual stability index (VSI) rating test method (PCI-TR-06, 2003) was proposed where a rating from 0 to 3, with 0 being no segregation and 3 being clear sign of segregation, was given after assessing the concrete patty after the slump flow test. As mentioned, this method is still inadequate as it relies on the experience and judgement of the operator and does not quantitatively assess the segregation of the mix, hence it has not been officially standardised. No quantitative test methods are currently available for evaluating the dynamic segregation of SCC. There is only one standardised test method, the sieve segregation test, for assessing the static segregation of SCC quantitatively.

2.2.3.3.1 Sieve segregation test

In this test (BS EN 12350-11, 2010), the static segregation is evaluated by measuring the amount of laitance passing through a 5mm sieve. The concrete is allowed to stand for a certain period of time and then a certain mass of the upper layer is poured onto the sieve where the amount of laitance passing the sieve is weighed and given as a percentage of the total weight of concrete poured called the segregation index. The more laitance passing through gives a higher segregation index indicating higher risks of segregation of concrete after placement.

For each of the SCC tests, classes of values have been published by EFNARC in report titled ‘The European Guidelines for Self-Compacting Concrete’ (2005) allowing users to easily specify, for a SCC mix, the classes they require for filling and passing ability and segregation resistance (Table 2-1). The use of additions in concrete is discussed in the next section.

Table 2-1 EFNARC classes for SCC (EFNARC, 2005; Testing-SCC, 2005)

Filling Ability		**Passing Ability**		**Segregation Resistance**	
Class	*Slump flow (mm)*	Class	*Blocking ratio of L-box*	Class	*Segregation index (%)*
SF1	550 – 650	PA1	≥ 0.80 (2 bars)	SR1	≤ 20
SF2	660 – 750	PA2	≥ 0.80 (3 bars)	SR2	≤ 15
SF3	760 – 850				
	V-funnel flow time (s)		*J-ring step height (mm)***		
VF1	≤ 8	PA1	≤ 15 (59 mm bar spacing)		
VF2	9 – 25	PA2	≤ 15 (41 mm bar spacing)		

** Values have been assumed from the Testing-SCC report

2.3 Hardened property tests

In addition to the fresh property tests mentioned above and two typical hardened mechanical tests i.e. compressive and cylinder splitting tests, non-destructive and durability tests were also performed on the specimens. This section describes the various tests available for the latter two.

2.3.1 Non-destructive tests

Testing of concrete structures after the concrete has hardened is often necessary for determining its suitability for its intended use. It would be ideal if such tests can be done without damaging the concrete. A range of tests are available from completely non-destructive i.e. no damage to concrete, such as Schmidt hammer, Ultrasonic pulse velocity and dynamic elastic modulus tests, to partially destructive i.e. where the concrete surface is partially damaged, such as taking cores, pull-out and pull-off tests, are available. These tests can be used to assess various properties such as the elastic modulus, strength and surface hardness. In addition they can be used to locate defects in concrete such as cracking, voids and honeycombing (Carino, 1994). Non-destructive tests (NDT) can be applied to both old and new structures and can be performed repeatedly allowing the continuous gathering of indirect information about in-situ concrete without damaging the concrete structural member. Hence these tests are more efficient as they can be performed repeatedly on the same specimen and also have a lower cost compared to other tests such as coring (partially destructive). It is known that there is a relationship between the NDT results and the strength of normal-consistence concrete (Domone & Illston, 2010).

2.3.2 Durability tests

Durability is one of the most important aspects in concrete design, ensuring satisfactory performance (given reasonable maintenance) throughout its service life in its environment. Durability maybe defined as the resistance of the concrete to weathering actions (such as freeze/thaw or wetting/drying cycles), chemical attacks (such as sulphate, acid or chloride attacks or alkali-silica reaction) and abrasion-erosion. As concrete is a porous material, the rate of many of these processes depend on the rate or ease at which fluids in the form of moisture (water), air (CO_2 and oxygen) and other aggressive ions (chlorides, sulphates) can penetrate or migrate through the concrete (Domone & Illston, 2010; Soutsos, 2010). There are three main transport mechanisms by which these substances can enter the concrete matrix, permeation (movement of fluid due to a pressure gradient), diffusion (movement of fluid due to a concentration gradient) and sorption (movement of fluid due to capillary suction).

Water acts as a carrier for the movement of aggressive ions in to the concrete hence having a concrete with good resistance to water penetration is very beneficial. The concrete cover is the first line of defence against penetration of harmful substances into the concrete and this is mainly dominated by sorption hence it is essential to have methods of measuring this (Page & Page, 2007).

Chloride ingress through the concrete cover could lead to corrosion of the reinforcement bars which in turn could lead to an unacceptable loss of serviceability. This is mostly the case for structures in marine environments or those exposed periodically to de-icing salts such as bridges; hence the resistance to chloride ion penetration is also an important property of the concrete in terms of durability (Soutsos, 2010; Domone & Illston, 2010; Neville, 2011). Various tests have been developed over the years to estimate the chloride resistance of concrete.

2.3.2.1 Water absorption tests

In this section some of the water absorption tests available are given.

Immersion test: In this test, the concrete specimens (cylinders or cubes) are cast and water cured until the time of testing. The specimens are then dried in the oven at 105±5°C for about 72 hours and then allowed to cool for 24 hours after which they are completely immersed in water (with 25±5mm of water above the top surface the specimen) for about 30 minutes. The specimens are weighed prior to and after immersion and the increase in mass is expressed as the percentage of the dry mass. The test procedures are described in BS 1881-122 (2011). The shortcomings of this test are that firstly the water movement is mainly due to permeation and not capillary absorption and secondly the high drying temperature can lead to micro cracking which could lead to unrealistically high absorption values. Other similar tests are available where the drying period and/or immersion periods are different however the concept being the same.

Sorptivity test: The water intake per unit area with time is referred to as sorptivity. Unlike the immersion test, in this test only one surface of the concrete is in contact with only a thin layer of water hence it is considered that capillary absorption is the dominant mechanism. According to Hall (1989), three different test set-ups can be used to measure the water absorption into a sample from a water reservoir.

- Horizontal inflow method: The water travels horizontally through the specimen and the absorption is dependent on the hydrostatic forces however independent of gravitational effects.

- Infiltration or ponding method: The water absorption is dependent on both capillary absorption and gravitational effects. Unlike the immersion test, the specimens are dried at around 70°C to prevent micro cracking and therefore avoiding unrealistically high absorption values. The top surface of the concrete is in contact with the water hence the pressure head will also have an effect on the absorption.

- Capillary rise method: Water is taken in from the bottom face of the specimen hence the capillary absorption opposes the gravitational forces. There are two versions of this test, in the first the test is performed on circular discs of 150 mm diameter with a thickness of 50 mm. The specimens are dried at approximately 105°C. Only one face of the specimen in contact with the water with other surfaces sealed. The absorption is determined by the weight changes of the specimen over time (RILEM TC 116-PCD, 1999). As with the immersion test, drying at such a high temperature could lead to micro crack formation and thus high absorption values. The second version is given in ASTM C 1585 (2013). The main differences is that here the tests are performed on circular discs of 100 mm diameter with a thickness of 50 mm and that the drying is done at 50°C preventing micro cracking giving more realistic absorption values.

2.3.2.2 Chloride resistance tests

This section discusses the range of tests available to give an indication of the chloride resistance (The Concrete Society, 2008; Stanish et al., 1997).

Movement of chloride ions in materials such as concrete are conventionally determined by complete immersion tests where the specimen is fully immersed in the salt solution such as bulk diffusion test (Nordest NT Build 443, 1995) or salt ponding test (AASHTO-259-80, 2002) or by use of diffusion cells such as the concentration difference test (Page et al., 1981); however these test could take several months to complete. In some cases i.e. for marine structures cores are drilled and removed at various depths from the structure and the chloride ion concentration measured by chemical analysis however this method is time consuming and expensive. On the positive, these are fundamental tests which only consider movement of chloride ions and are not affected by external sources.

Given the shortcomings of the above tests, mainly the long duration which makes them unsuitable for use in quality assurance, accelerated tests have been developed which take less time. One such test is the Rapid Chloride Penetration (RCP) Test which was first developed by Whiting (1981). The standardised test procedures are given in ASTM C1202 (2007) and AASHTO T 277 (2007). This test involves placing a circular disc (100mm diameter and 50mm thickness) between two charged cells, one containing a chloride solution and the other a hydroxide solution, and accelerating the diffusion process by applying a potential difference of 60 volts for 6 hours. The total amount of charge passed (area under current-time graph) would give an indication of the chloride resistance of the concrete with a low value of charge indicates good resistance and vice versa. Initial researchers found a good correlation between the values of charge passed and the 90-day ponding test. However, over the years, some researchers have shown concerns and criticised the ability of the RCP test in evaluating the chloride penetration and permeability of the concrete (Feldman et al., 1994; Sherman et al., 1996; Shi et al., 1998; Shi, 2004). The main criticisms are:

- The high voltage applied leads to a temperature increase in the specimen. This in turn results in increased conductivity hence higher value of charge passed. This is less of a problem for high quality concrete but more of an issue for low strength/low quality concrete.

- The value of the current passed is actually related to all ions in the pore solution and not solely to chloride ions. Hence the addition of supplementary cementitious materials such as ggbs and fly ash can change the chemistry of the pore solution to the extent of affecting the RCP results.

2.4 Binary blended binders

An addition is defined as a ‘finely divided material used in concrete in order to improve certain properties or to achieve special properties’, the standard defines two distinct types: Type I (nearly inert) addition and Type II (pozzolanic or latent hydraulic) addition (BS EN 206-1, 2000).

Type I additions are nearly inert hence only act as fillers and do not participate in the cement hydration reaction. A pozzolanic addition (also known as a pozzolana) is defined as a silica (SiO_2) rich material which possesses little or no cementitious property in itself but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form cementitious compounds (ASTM C618-12, 2012).

Pozzolanic additions used in concrete could be characterised by their high amorphous silica content, surface area (finer particles have a faster rate of reaction than coarser particles), particle shape and also the contents of calcium oxide (CaO) and aluminium oxide (Al_2O_3), all of which affect the reactivity of these additions. The Portland cement hydration reaction results in the formation of calcium-silicate hydrates (C-S-H), responsible for giving concrete its strength, and calcium hydroxide ($Ca(OH)_2$), also known as portlandite. The SiO_2 and Al_2O_3, two of the major oxides in additions, react with the $Ca(OH)_2$ from the cement hydration, forming further C-S-H and calcium aluminate hydrates respectively (the pozzolanic reaction). These complement those already formed by the cement hydration, filling voids and leading to the formation of a denser concrete matrix with advantages such as improvement in long-term strength and improved durability.

The effectiveness of additions in terms of concrete strength gain varies from one to another depending on the pozzolanic reactivity of the addition which in turn depends on various aspects such as chemical composition, fineness and also replacement levels of the addition. However at normal temperatures, the reaction between the cement and the pozzolanic additions is usually slow though the reactivity could be improved by methods such as improving the fineness of the addition by further grinding (mechanical), increasing the hydration reaction rate by curing at higher temperatures (thermal) and also the reactivity could be increased by adding chemicals (chemical).

Over the past two decades, various additions have been utilised in concrete, a number of them are listed in Table 2-2. A detailed review of some of the more commonly used additions i.e. ggbs, fly ash and limestone powder, in concrete is given in sections 2.4.1, 2.4.2 and 2.4.3 respectively.

Table 2-2 List of additions utilised in concrete

Additions	
Manufactured	**Natural**
Ground granulated blast furnace slag	Limestone powder
Steel slag	Marble Dust
Fly ash	Quarry Dust
Incinerator Bottom Ash	
Non-ferrous metal slag	
Sewage Sludge Ash	
Wood Ash	
Paper Sludge Ash	
Asphalt Plant Dust	
Metakaolin	
Silica Fume	
Rice Husk Ash	

2.4.1 Ground granulated blastfurnace slag

Blastfurnace slag is a by-product of the manufacture of iron in a blastfurnace and it results from the fusion of a limestone flux with coke and iron ore. The furnaces operate at a temperature of about 1500°C and are carefully fed with iron-ore, limestone and coke. The iron-ore is then reduced to iron and the remaining materials form a slag on top of the iron, which is then removed as molten liquid and rapidly quenched in large volumes of water. The quenching forms granules which are in turn ground to a fine powder to produce ggbs (UKCSMA, 2012). After quenching the molten slag, the size of the granules formed range from 100mm to dust, with the larger particles being crystalline in nature and having very little or no cementitious value, hence the particles larger than 6mm are used as lightweight aggregates in concrete to make lightweight concrete blocks and all other particles are ground to a fine powder producing ggbs which is used as a cement replacement material within concrete (Newman & Choo, 2003). The potential of ggbs was discovered in 1862 in Germany by Emil Langen and in 1880 it was first used in combination with Portland cement. Since then it has been extensively used throughout the world, with the UK producing its first British Standard for Portland Blastfurnace Cement (PBFC) back in 1923 (Newman & Choo, 2003).

Each year over 2 million tonnes of ggbs are produced in the UK. The vast majority of this is used as a cementitious addition in both ready mixed and precast concrete resulting in a reduction in carbon dioxide emissions and saves a potential landfill of two million tonnes (MPA, 2012). Hence it is advantageous in terms of sustainability to use ggbs as a partial replacement for the Portland cement in concrete (UKCSMA, 2012; Higgins, 2006). Using ggbs as a cement replacement material has many advantages such as lower heat of hydration (reducing risk of thermal cracking), lower permeability in the concrete, improved workability (making placing and compacting easier), better durability (eliminating the risk of alkali silica reaction taking place) and higher long-term strength of the concrete (UKCSMA, 2012; Osborne, 1999).

Table 2-3 Typical chemical composition of ggbs (UKCSMA, 2012)

Chemical composition	(%)
SiO_2	30
Al_2O_3	13
CaO	40
MgO	8
Other minor oxides	4

The utilisation of ggbs as a Portland cement replacement is well established and a wealth of information has been reported within the literature over the past 30 years. Blastfurnace slag is a hydraulic addition (Type II addition) conforming to BS EN 15167-1 (2006) and contains significant amount of CaO (Table 2-3), meaning that it can react directly with water forming C-S-H gels, hence it is not a true pozzolan. However on itself ggbs hardens very slowly but is activated by combining it with Portland cement with the $Ca(OH)_2$ from the cement acting as a form of catalyst. Typical replacement levels are up to about 50% but levels of up to 95% are possible (BS EN 197-1, 2011). The effects of ggbs on the fresh, hardened mechanical and durability properties of concrete are discussed below.

2.4.1.1 Fresh properties

Concrete mixes with ggbs have similar or albeit slightly higher consistence (lower water demand) compared to that of Portland cement mix, which is attributed to better dispersion of cementitious materials and also to the smooth surface of ggbs particles (Neville, 2011). In addition, mixes with ggbs tend to require less energy for flow to occur (lower yield stress) making easier to place and compact the concrete (UKCSMA, 2012).

2.4.1.2 Early age properties

The setting time depends on many factors such as temperature and water/cement ratio but generally the final setting time of ggbs concrete is extended by about 30 minutes compared to Portland cement concrete (UKCSMA, 2012; The Concrete Society, 2011). This means that the concrete will stay workable for a longer period which could be an advantage in some cases like reducing the risk of cold joints especially in warm weather. In the study by Mounanga et al (2011) the final setting time of a mix with 25% ggbs is 556 minutes compared to 537 minutes for the control mix with no change in the initial setting time. However it shows that the final setting time for a mix with 50% ggbs is 467 minutes which is a reduction of about an hour, again with no change in the initial setting time. This has been explained by the dilution effect, where at that level of ggbs replacement, there is more water available to hydrate the Portland cement and the ggbs particles act as nucleation sites for the hydration products hence accelerating the hydration process leading to the reduction in the final setting time (Escalante-García & Sharp, 1998;

De Schutter & Taerwe, 1995). However this is contradicted by Wainwright & Ait-Aider (1995) where they tested a range of mixes with ggbs replacement levels of 40% and 70% made with cement obtained from three different sources and observed an increase in both the initial and final setting time of all the mixes.

The addition of ggbs reduces the amount of cement available to hydrate. It is the primary hydration reaction between Portland cement and water which is highly exothermic hence replacing part of the cement with ggbs leads to a reduction in the heat of hydration, due to the dilution effect and the slower hydraulic reaction, of the concrete resulting in reduced risk of thermal cracking (Mounanga et al., 2011; UKCSMA, 2012). The addition of 25% and 50% of ggbs resulted in the reduction in peak heat output rate of 21% and 53% respectively as shown in Figure 2-1 (Mounanga et al., 2011). A similar trend was also obtained by Ballim & Graham (2009) and Wang & Lee (2012).

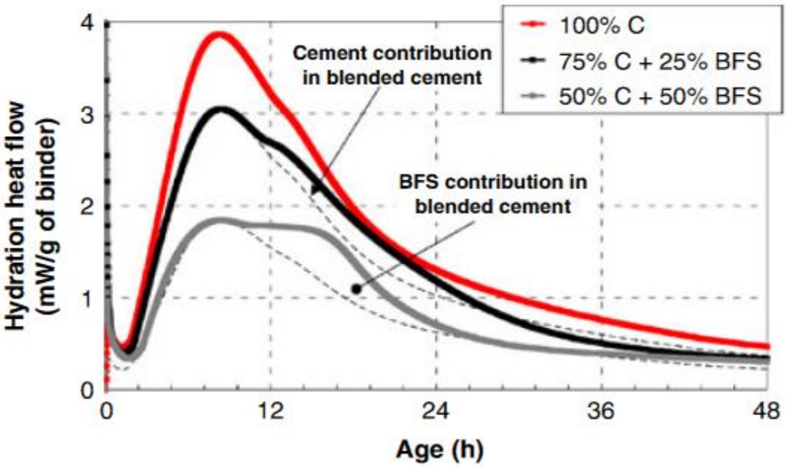


Figure 2-1 Hydration heat output rate for ggbs concrete (Mounanga et al., 2011)

2.4.1.3 Strength

Concrete made with ggbs usually has a lower early-age strength compared to that made with pure Portland cement but, at later ages the strength of the ggbs concrete surpasses that of Portland cement concrete (UKCSMA, 2012). There is less Portland cement available to hydrate and the slow reaction rate of ggbs and so the initial hydration reaction rate of the matrix is slower hence the low early-age strength. The secondary reaction of the ggbs takes place within cement matrix between ggbs and the calcium hydroxide, forms a finely dispersed gel filling the large pores within the paste matrix giving the higher long-term strength.

These effects are illustrated in Figure 2-2, in which the early-age strength of ggbs concrete is lower than the control mix (up to 28 days) and then at later ages, in case of the mixes with 40% and 60% replacement, the strength surpasses that of the control mix. Also the rate of strength development within the ggbs concrete is higher after 28 days than that of the control mix. At a ggbs replacement level of 80%, the strength of the concrete is lower than the control mix at all ages which is due to the fact that there is insufficient calcium hydroxide produced from the cement hydration to form further C-S-H, hence an optimum replacement level of about 40-50% is typically used.

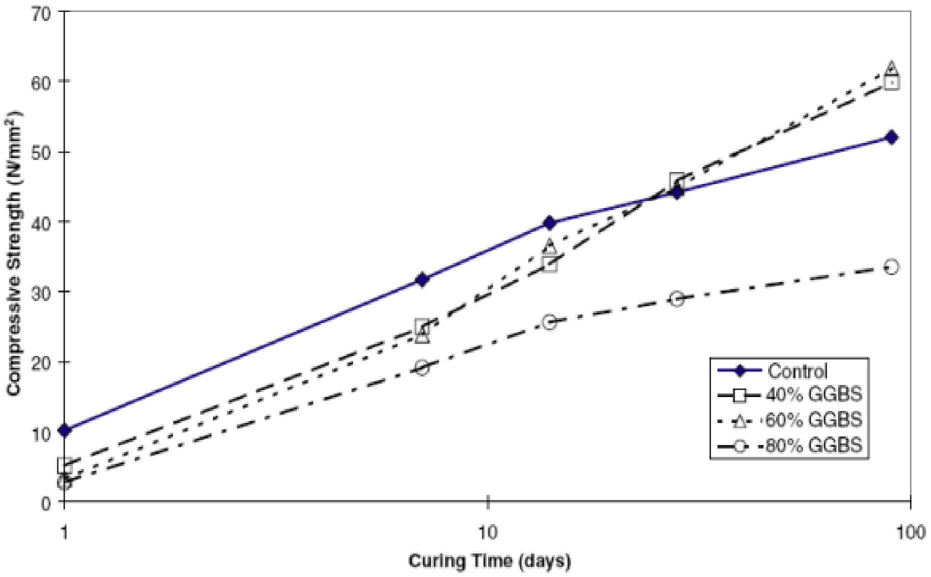


Figure 2-2 Effect of ggbs replacement on compressive strength (Khatib & Hibbert, 2005)

Roy & Idorn (1982) reported that for a ggbs replacement range of 20-60%, the positive effects on compressive strength did not occur until after 28 days of curing after which similar or higher compressive strengths were obtained. This is in agreement with the trend observed in Figure 2-2. Megat Johari et al. (2011) and

Uysal et al. (2012) performed tests on self-compacting concrete and also observed similar trends.

Khatib & Hibbert (2005) also looked at the effect of ggbs on the flexural strength of concrete and noticed a slight increase (5.8MPa compared to 4.8MPa) at 60% ggbs replacement whereas at addition levels of 40% and 80% the flexural strength of the concrete was lower than the control mix (4MPa and 2.8MPa respectively). The study by Guneyisi and Gesoglu (2008) reported that the tensile splitting strength of ggbs concrete (50% replacement) is lower than that of reference Portland cement concrete at 28 days (3.93MPa compared to 4.41MPa); however it exceeded it at 90 days (5.20MPa compared to 5.09MPa) which is similar to the trend seen in the compressive strength of the concrete.

2.4.1.4 Durability properties

As mentioned above, when ggbs is added to Portland cement the secondary hydration reactions produce a finely dispersed gel which fills the large pores. The resultant hardened cement paste then has a greater number of smaller gel pores and fewer calcium hydroxide crystals and hence fewer larger capillary pores. This finer pore structure gives ggbs concrete a lower permeability than Portland cement concrete and makes it chemically more stable by limiting the ability of aggressive chemicals entering the pore structure. Çakır & Aköz (2008) reported that the porosity of mortar mixes decreased with increased slag replacement and also that the decrease was more profound in those specimens cured in water at 20°C than those cured at 40°C with 100% relative humidity.

The results obtained by Megat Johari et al. (2011) showed that the inclusion of ggbs significantly reduced the percentage of macro-pores (>50nm) and increased the percentage of meso-pores (range of <15nm to 50nm). The permeability of ggbs concrete is also lower compared to ordinary Portland cement concrete. Cheng et al. (2005) reported that pure Portland cement mix (Mix A in Figure 2-3) (w/c 0.55) had permeability of about $2.5\text{x}10^{-13}$ m/s whereas mixes with 40 and 60% ggbs replacement (Mixes B and C) had permeability of $1.5\text{x}10^{-13}$ m/s and $1.35\text{x}10^{-13}$ m/s respectively.

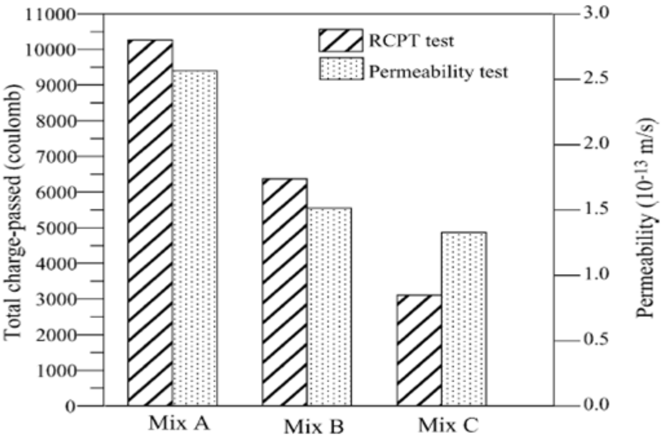


Figure 2-3 Permeability and total charge-passed for ggbs concrete (Cheng et al., 2005)

Figure 2-3 also shows that the total charge passed in a rapid chloride penetration test (described in Chapter 4) is lower for ggbs concrete which indicates a better resistance of ggbs concrete mixes to chloride ion penetration. The total charge-passed dropped from almost 10500 coulombs for Mix A to about 6500 and 3000 coulombs for Mixes B and C respectively. Again, this could be attributed to the finer pore structure of ggbs concrete. Uysal et al. (2012) also reported similar trend in total charge passed in self-compacting concrete mixes with varying ggbs replacement of 20, 40 and 60%. In addition, replacing part of the cement with ggbs increases the chloride binding capacity of the mix, which is the amount of chloride ions that can bind to the hydrated cement products, reducing the amount of 'free' chloride ions (Dhir et al., 1996; Xu, 1997; Arya & Xu, 1995; Vejmelková et al., 2009). Dhir et al. (1996) reported that the chloride binding capacity of mix with 67% ggbs replacement was 5 times than that of Portland cement control mix. The binding capacity is proportional to the ratio of chloride to hydroxide ions (Cl^-/OH^-) in the cement pore solutions (Arya & Xu, 1995; Dhir et al., 1996). It is the 'free' chloride ions which are able to react within the concrete hence a mix with a higher chloride binding capacity would have greater resistance against chloride-related durability issues such as corrosion of reinforcement bars.

The study by Adam et al. (2010) show that the sorptivity of concrete mixes containing 0, 30, 50 and 70% ggbs decreases with the increase in ggbs content. The sorptivity coefficient was lower at 91 days compared to that at 28 days for the first three, but the opposite was the case for the mix with 70% ggbs replacement (0.085 and 0.1 mm/min$^{1/2}$ at 28 and 91 days respectively). Elahi et al. (2010) tested concrete containing 0, 50 and 70% ggbs replacement obtaining the sorptivity coefficient, which is the gradient of the linear relationship between water intake per unit area and the square root of time, at 44 and 91 days. The mix with 50% ggbs replacement yielded lower sorptivity coefficient values, at both 44 and 91 days, of 77.1 and 96.9% respectively relative to the control mix. Increasing the ggbs replacement to 70% significantly increased the sorptivity coefficient at both ages (44 and 91 days) to 120.1 and 103.8% respectively.

Ggbs concrete can resist attack by sulphates much better than Portland cement concrete (Gallop & Taylor, 1996; Fearson, 1986; Higgins & Crammond, 2003; Uysal & Sumer, 2011; Atahan & Dikme, 2011; Gruyaert et al., 2012). Sulphates react with the C_3A and $Ca(OH)_2$ in the concrete to form an expansive compound called secondary ettringite which could cause cracking and gypsum respectively (Neville, 2011; Siddique & Bennacer, 2012). Since ggbs does not contain any C_3A the replacement of Portland cement with ggbs reduces the total C_3A content of the mix, having said that it is important to also account for the alumina in ggbs. The recommended alumina content is less than 14%, if this is exceeded, then a Portland cement with a low to moderate C_3A (less than 10%) content should be used (Osborne, 1999). The $Ca(OH)_2$ reaction with the ggbs described above, reduces the amount of $Ca(OH_2)$ crystals available to form gypsum. In addition, the lower permeability of ggbs concrete also limits the penetration of sulphates into the cement matrix. Uysal & Sumer (2011) looked at the compressive strength loss of two sets self-compacting concrete specimens, one immersed in 10% magnesium sulphate solution and another immersed in 10% sodium sulphate solution. After 400 days exposure in magnesium sulphate solution, the loss in compressive strength for the Portland cement mix was 13% whereas mixes with 20, 40 and 60% ggbs replacement had losses of 5.5, 4.5 and 4.7% respectively. The compressive strength losses were lower for the specimens immersed in sodium sulphate solution with the Portland cement mix standing at 9.5% and the ggbs mixes at 3.5, 1.5 and 3.7%

respectively. In both cases the mix with 40% ggbs replacement performed better than others having the lowest strength loss. Another study looked at the expansion of mortar mixes made with sulphate contaminated sand (2% water soluble sulphate by weight) immersed in calcium hydroxide solution (Atahan & Dikme, 2011). The expansion of the reference Portland cement mix, after 12 months immersion period, was about 0.55% compared to 0.18, 0.09 and 0.08% for mixes containing 20, 40 and 60% ggbs replacement.

Another durability concern with concrete is Alkali-Silica Reaction (ASR) which is a chemical reaction between the alkalis (basic oxides which form hydroxide ions (OH^-) when dissolved in water) in the cement and certain types of silica in the aggregates. It results in the formation of expansive gels which lead to cracking of the concrete and unfortunately the cycle continues until the concrete is no longer serviceable. The addition of ggbs reduces the alkalinity of the concrete, as the alkaline content of ggbs does not contribute to the total reactive alkali, hence reducing the alkali-silica ratio (Neville & Brooks, 2010; Lindgård et al., 2012). It also reduces the mobility of alkalis with the concrete due to its finer pore structure and in addition it reduces the amount of free lime (calcium oxide) in the concrete which is an important factor for ASR. A number of studies have been done on looking at the effect of ggbs addition on the ASR expansion of concrete specimens and all conclude that the addition of ggbs leads to reduction in ASR expansion (Lumley, 1993; Maier & Durham, 2012; Hester et al., 2005; Bleszynski et al., 2002). In their study Maier & Durham (2012) showed that the longitudinal expansion of concrete prisms made from purely Portland cement was about 0.3% at two weeks compared to 0.02% for specimens containing 50 and 100% ggbs replacement. Their results show that the expansion for mix with 50% ggbs replacement is the same as that with 100% ggbs replacement; hence the inclusion of ggbs at a replacement of greater than 50% results in the elimination of damaging expansions in concrete. This has been confirmed by numerous field and laboratory studies that have been done regarding ASR expansion in mixes incorporating ggbs and it is generally accepted by the construction industry that the inclusion of ggbs of 50% or more eliminates the harmful effects of ASR.

In summary, the utilisation of ggbs improves the durability of concrete however the degree of improvement very much depends on, as seen, the ggbs replacement level. There are therefore recommended replacement levels for the different durability issues discussed. It is recommended that replacement levels of higher than 50% would eliminate the harmful effects of ASR, as mentioned, however for concrete mixes which to have a high chloride or sulphate resistance, replacement levels above 66% are recommended (UKCSMA, 2012).

2.4.1.5 Improving the reactivity of blastfurnace slag

One clear disadvantage of using high replacement levels (>50%) of ggbs is the lower strength and slow strength gain at early age because of the slow rate of reaction between ggbs and $Ca(OH)_2$. Hence to be able to further promote the use of high replacement levels it is necessary to tackle issues regarding the low strength, especially at early age. As mentioned in section 2.4, three methods are commonly used to improve the reactivity of ggbs, these are briefly explained below.

Mechanical treatment: Wan et al (2004) studied the effect of the geometric characteristics of ggbs particles on its activity index and the fluidity and the compressive strength of a mix having 50% ggbs replacement by weight. They concluded that the compressive strength of the mix depends on both the specific surface area (SSA) and the particle size distribution (PSD) of the ggbs. Higher strength is achieved with the ggbs having a greater surface area; when ggbs with same surface area is used a higher the proportion of fine particles (<3µm) improves the early strength (increasing fineness increases the rate of reaction) whereas with ggbs containing a higher proportion of particles in the range of 3-20µm, the long-term strength was improved. This was confirmed by Kumar et al. (2008).

Thermal treatment: The effect of curing conditions on the compressive strength of mortars with and without ggbs was studied by Çakır & Aköz (2008). Three ggbs replacement levels were considered, 0, 30 and 60% by weight with one set of specimens cured in water at 20°C and another set in a humidity controlled cabinet at 40°C with almost 100% relative humidity. The 7-day compressive strength of the mixes cured in water at 0, 30 and 60% ggbs replacement was 33.7, 31 and 26.3MPa respectively whereas those cured at elevated temperatures had compressive strengths of 36.9, 34.1 and 32.6MPa respectively. The compressive strength increased with time for both curing conditions however at later ages (28 and 180 days) those specimens cured in water had higher strengths relative to those cured at elevated temperatures. Elevated temperatures do increase the rate of hydration reaction (higher strengths at 7 days) however this resulted in a lower long-term strength which could be due to the fact that at elevated temperatures, due to the increased rate of hydration, the calcium silicate hydrates formed are less uniform and hence weaker than those produced at lower temperatures. Similar conclusions were drawn by Barnett et al. (2006).

Chemical treatment: Increasing the alkalinity of the pore solution can lead to an increased rate of pozzolanic reaction with ggbs and to achieve this it is necessary to add an alkaline solution to the mix (Pacheco-Torgal et al., 2008). Due to its latent hydraulic nature, blastfurnace slag is said to be the first cementitious material that was activated by alkali, with the first studies believed to have been done by Feret (1939) and Purdon (1940). Since then, with the environmental issues of Portland cement and the search for alternative binders, researches from around the world have shown increasing interest in this ‘alkali-activated slag’ (AAS) (Wang et al., 1994; Wang & Scrivener, 1995; Collins & Sanjayan, 1998; Collins & Sanjayan, 1999; Al-Otaibi, 2008; Atiş et al., 2009; Puertas et al., 2009; Escalante-Garcia et al., 2009; Chi, 2012; Sajedi & Abdul Razak, 2011). The main role of the alkalis in AAS is, as in Portland cement-ggbs blended cement, to supply the hydroxide ions (OH^-) in the system, with the main hydration product being C-S-H gels which contribute to the strength of concrete (Shi et al., 1991; Wang & Scrivener, 1995). In ggbs blended cements, the OH^- ion is provided by the $Ca(OH)_2$ produced from the hydration of Portland cement and is capable of breaking down the coating formed around ggbs when mixed with water; however, at high levels of replacement, there is insufficient $Ca(OH)_2$ produced and hence another source of alkali is needed (Taylor, 1997). Some of the common chemical activators used are high concentration of $Ca(OH)_2$, sodium hydroxide (NaOH), sodium sulphate ($NaSO_4$), sodium carbonate (Na_2CO_3), potassium hydroxide (KOH) and sodium silicate (water glass) (Na_2SiO_3). Many studies reported that the use of sodium silicates or a blend of sodium silicate with NaOH gave the highest strength results relative to the use of other activators. The result obtained by Shi (1996) on AAS mortars (activator dosage of 6% by mass of Na_2O) is shown in Figure 2-4. The results show that using sodium hydroxide as the activator yielded lower compressive strength than the reference Portland cement mix at all ages, with sodium carbonate the mix gave equivalent strength to the reference mix only at 180 days whereas using sodium silicate gave higher strength results than the reference mix at all ages.

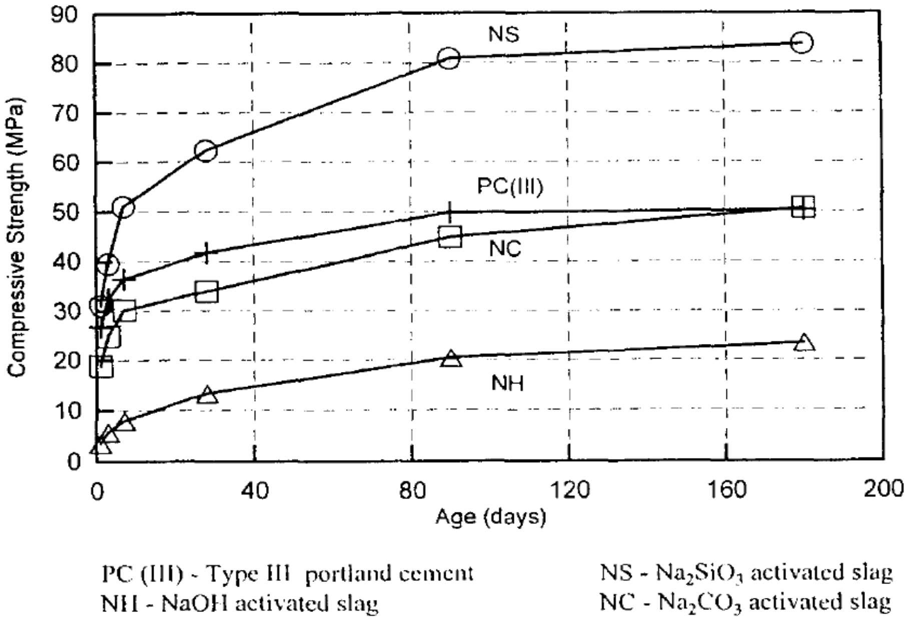


Figure 2-4 Strength development of AAS mortars with different activators (Shi, 1996)

However it also must be noted that the performance of AAS mixes also depends on the activator dosage (Acevedo-Martinez et al., 2012; Ravikumar & Neithalath, 2012). This is illustrated in Figure 2-5. With no activator it can be noticed that as ggbs replacement increases the early strength reduces, however when 4% Na_2O is used (waterglass (Na_2SiO_3) used as activator) the strength of the mix with the highest ggbs replacement (80% in this case) is higher than the mixes with lower ggbs replacement. Also the rate of strength gain seems to increase as the concentration of the activator is increased, for example for the mix with 80% ggbs replacement, the strength at 28 days, with 0, 4, 6 and 10% activator is 15, 25, 45 and 85MPa respectively, whilst the control Portland cement mix had a strength of 30MPa at the same age. However it is important to note that the reaction mechanisms of AAS are very complex and not quite fully understood as it depends on many factors such as (Pacheco-Torgal et al., 2008; Fernández-Jiménez et al., 1999; Shi et al., 2006):

- The chemical and physical properties of the slag
- The chemical nature and dosage of the activator
- Water/slag ratio and modulus ratio of solution
- Curing temperature

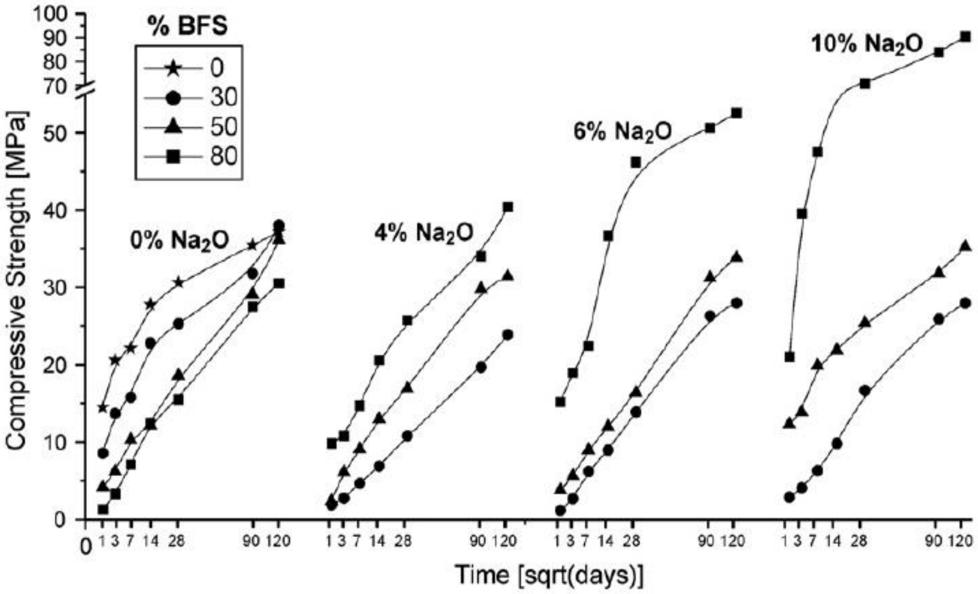


Figure 2-5 Compressive strength of non-activated and Na_2SiO_3-activated slag mixes with different activator concentration (Acevedo-Martinez et al., 2012)

2.4.2 Fly ash

The electricity produced through coal burning supplies about 40% of the UK electricity demand (UKQAA, 2007). Fly ash (FA) (also known as pulverised fuel ash-pfa) is a by-product of the combustion of coal in power stations; it is a fine powder which is grey in colour (similar to Portland cement) and it is carried out of the furnace by waste gases following the combustion of the coal. It is the minerals, deposited millions of years ago, in the coal, that when burned at a temperature of 1250°C in the furnace, produce the ash. Due to the high temperature, the ash is carried with the gas stream and subsequently extracted from the stream using electrostatic precipitators (Sear, 2001; UKQAA, 2012). There are four types of fly ash available in the UK (Sear, 2001):

1. Dry ash – ash taken directly from the silos at the power station
2. Conditioned ash – dry ash, taken directly from the silos at the power station, to which a certain amount of water has been added to give the optimum moisture state
3. Stockpile ash – conditioned ash that has been stockpiled prior to its use
4. Lagoon ash – ash that has been slurried, pumped to storage lagoons, allowed to drain and subsequently recovered

Annually, within the UK, around 6 million tonnes of fly ash is produced (either in the form of dry, lagoon, conditioned or stockpile) with only half being utilised with the remainder sent to landfill (Sear, 2001; UKQAA, 2007). According to UKQAA (UKQAA, 2012), in 2011, about 59% of the fly ash utilised was used in the construction industry. In addition to the annual production there is also a considerable amount of stockpile ash which is readily available. Fly ash (mainly the dry form), has been extensively used throughout the world as a Type II addition in concrete, replacing some of the Portland cement. BS EN 450-1 (2012) identifies two categories of fly ash based on its fineness:

- Category N: ≤ 40.0 % retained on the 45μm sieve
- Category S: ≤ 12.0 % retained on the 45μm sieve

Another well-known classification is given by the American Society for Testing and Materials (ASTM) where the fly ash is classified according to the type of coal and the total content of SiO_2, Al_2O_3 and Fe_2O_3, documented in ASTM C618-12 (2012):

- Class F: made from bituminous or anthracite coal, oxide content $\geq 70\%$
- Class C: made from lignite or subbituminous coal, oxide content $\geq 50\%$

Class F fly ash is a pozzolanic material whilst Class C fly ash, in addition to having pozzolanic properties, also exhibits some self-cementing property as it contains a higher CaO content (≥ 20%). Only Class F fly ash, for use in concrete, is available in the UK (Sear, 2001).

Fly ash can also be utilised in concrete as filler aggregates (Type I addition) in accordance with BS 12620 (2002) and as a lightweight aggregate in accordance with BS EN 13055-1 (2002). The lightweight aggregate, known as lytag, is made by pelletising the fly ash, adding a controlled amount of water to it and then heating on a sinter strand to a temperature of about 1100°C, forming a hard, honeycombed structure of interconnecting voids within the aggregate (Lytag, 2012). Lytag has been used in concrete to produce lightweight concrete by replacing the natural coarse aggregates. Some of the advantages of using lytag are low density (lighter weight), good thermal insulation and also good sound insulation properties (Lytag, 2012). However due to the interconnecting voids, Lytag has higher water absorption than natural aggregates, coupling this with the lower density of the aggregate, the concrete produced using Lytag has a lower compressive strength than normal concrete.

In addition to utilising fly ash as partial replacement of the cement and as a lightweight coarse aggregate, some researchers have also looked at using fly ash as partial replacement of the fine aggregate (sand). Siddique (2003) produced extensive data on effects of replacements of fine aggregates with fly ash with a replacement range of 10 – 50% by weight of sand, concluding a reduction in the workability of the concrete and an improvement in the compressive strength of the concrete. A similar result was obtained by Dhir & McCarthy (2000) and Mangaraj & Krishnamoorthy (1994). A recent paper by Rajamane et al. (2007), using previous literature, successfully attempted to produce a formula predicting the strength of the concrete considering different replacement levels of the sand with fly ash.

Table 2-4 Typical range of chemical composition of Class F fly ash

Chemical composition	(%)
SiO_2	38 – 52
Al_2O_3	20 – 40
CaO	1.8 – 10
Fe_2O_3	6 – 16
MgO	1.0 – 3.5
K_2O	2.3 – 4.5
SO_3	0.35 – 2.5
TiO_2	0.9 – 1.1
Na_2O	0.8 – 1.8
Other minor oxides	0.01 – 1.0

Unlike ggbs, Class F fly ash is a true pozzolanic material, meaning it is silica (SiO_2) rich (Table 2-4) and shows very little pozzolanic reaction at early ages, hence when used as an addition replacing part of the Portland cement, the concrete will have a lower early-age compressive strength compared to concrete with Portland cement as the sole binder. Due to this fact, the replacement levels of fly ash within concrete vary from 10 – 80% with an optimum replacement level being only about 30% which is based on the fact that sufficient $Ca(OH)_2$ must be produced, by the initial reaction between Portland cement and water, to react with the silica in fly ash to give the cementitious compounds. The effect of fly ash on concrete performance, as a Type II addition, is discussed below.

2.4.2.1 Fresh properties

The spherical shape of fly ash particles leads to improved particle packing and easier particle movement in the mix, hence a reduction in the water demand i.e. higher consistence. Jiang & Malhotra (2000) reported in their study that a 55% fly ash replacement resulted in a water demand reduction of about 20%. Nanthagopalan et al. (2008) showed that for concrete with water/powder ratio of 1.5 (by volume), by replacement of 10%, 20% and 30% fly ash, the slump flow increased from 220mm to 255mm, 270mm and 290mm respectively, hence for mixes with superplasticiser addition, with the inclusion of fly ash, a lower dosage will be required to obtain the same mix consistence which can lead to cost savings.

2.4.2.2 Early age properties

In terms of the setting time, the addition of fly ash prolongs both the initial and final setting time of the cement paste (Mounanga et al., 2011). The amount of cement in the mix is reduced (dilution effect) resulting in a decreased rate of production of hydrates within the mixture hence delaying the setting and hardening of the cement paste. The final setting time of fly ash concrete with 25 and 50% replacement level is 657min and 681min respectively compared to 537min for the control mix (Mounanga et al., 2011). This is also mirrored in the results obtained by Gesoğlu & Özbay (2007). This effect can also be seen in Figure 2-6 as the addition of 25 and 50% fly ash results in a delay of peak heat flow of about 88 and 118min respectively.

As with ggbs, the addition of fly ash reduces the rate of hydration reaction at early ages, as the amount of cement available to hydrate is reduced hence the heat of hydration of fly ash concrete is less than Portland cement concrete (Mounanga et al., 2011; Wang & Lee, 2012; Ballim & Graham, 2009; Schindler & Folliard, 2005). This is illustrated in Figure 2-6.

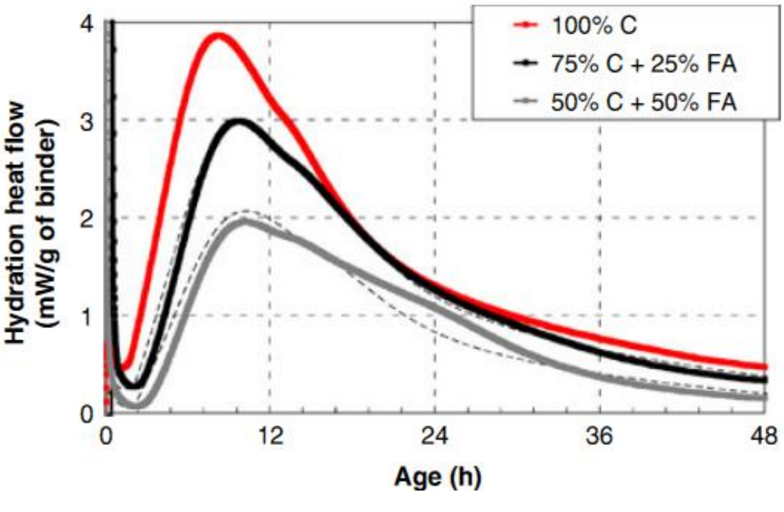


Figure 2-6 Hydration heat output rate for Class F fly ash concrete (Mounanga et al., 2011)

2.4.2.3 Strength

Fly ash, on its own, shows very little pozzolanic activity, hence the compressive strength of fly ash concrete is lower compared to Portland cement concrete at early ages (<28 days). Unlike ggbs, fly ash does not react directly with water (primary reaction) to form cementitious compounds but it does take part in the secondary pozzolanic reaction described earlier hence contributing to the long-term strength of the concrete (>28 days). The strength of fly ash concrete improves with age. Uysal & Sumer (2011) found the strength of mix, with 25% fly ash replacement, at 7, 28 and 90 days to be 61.4, 73.4 and 86.3MPa respectively. Li and Zhao (2003) reported that the compressive strength of concrete with 40% fly ash replacement, at 112 days, had strength of 97.5MPa compared to 91.2MPa for Portland cement concrete, hence this agrees with the generally accepted assumption that the compressive strength of fly ash concrete (at replacement levels up to 40%) exceed that of Portland cement concrete at later ages (Megat Johari et al., 2011; Elahi et al., 2010; Sumer, 2012; Uysal & Sumer, 2011; Hannesson et al., 2012). However Siddique (2004) shows that the compressive strength of concrete with 40% fly ash replacement does not exceed that of Portland cement concrete up to the age of 365 days.

The effect of fly ash on the strength of concrete is dependent on the water/binder ratio. (Poon et al., 2000; Lam et al., 2000; Bijen & Van Selst, 1993). Lam et al. (2000) observed that there was a reduction in the compressive strength at 28 days in the mix with 55% fly ash replacement at water/binder ratio of 0.5 of about 40%, whereas, at the same replacement level, the mix with water/binder ratio of 0.3 had a reduction of 30% compared to the control mix. However when comparing water/binder ratios 0.24 and 0.19, the reduction in 28-day strength, with 45% fly ash replacement, was 10 and 20% respectively, hence in this case lowering the water/binder ration did not improve the strength. Therefore it can be concluded that the strength of fly ash mixes can be improved, to some extent, by lowering the water/binder ratio.

The amount of calcium oxide (CaO) also has a significant effect on strength gain. Generally low-calcium fly ash (<10% total CaO) consist mostly of aluminosilicate-type glass and no crystalline compounds of calcium whereas fly ash with higher CaO content (>15%) has substantial crystalline compounds in the form of C_3A, C_4A_3S, CS and CaO in addition to aluminosilicate-type glass (Manz, 1999). Due to this Class C fly ash is more reactive than Class F fly ash as it can form cementitious compounds without the need for $Ca(OH)_2$. The increased reactivity of Class C fly ash leads to a higher early strength compared to Class F fly ash, Yazıcı et al. (2005) obtained higher strengths relative to the reference Portland cement mix as early as 7 days. For Class C fly ash replacement of 10, 20 and 30%, the 7-day strengths were 38, 45 and 43MPa respectively compared to 30MPa for the Portland cement mix which is not the case when using Class F fly ash. However at later ages, due to the slower reaction and better formation of the C-S-H crystals, the compressive strengths of mixes with Class F fly ash are higher than those with Class C fly ash of the same replacement level. Sumer’s (2012) results show that with 17% replacement of Class C fly ash, the compressive strengths at 28 and 90 days were 58.87 and 68.65MPa respectively whereas with Class F fly ash, at the same replacement level, the strengths were 55.27 and 69.79MPa respectively. The 28-day strength of mix with Class C fly ash is higher compared to that with Class F fly ash however at 90 days the opposite is the case.

The tensile splitting strength of fly concrete mixes show similar trends to the compressive strength, with the ratio between the values ranging from 8-10% for normal strength concrete, however this ratio is dependent on multiple factors such as aggregate type, age of concrete and curing conditions (Neville, 2011; Sukumar et al., 2008). Sata et al. (2007) obtained the ratio between the tensile and compressive strength of high-strength concrete to be between 6.3 and 6.9% which is lower than the ratios obtained for normal medium-strength concrete, concluding that the higher the compressive strength the lower the ratio between these two values. Similar trends were observed in other studies (Haque & Kayali, 1998; Shannag, 2000; Lam et al., 1998).

2.4.2.4 Durability properties

The spherical shape of fly ash particles result in a better packing and a reduction in water requirement, thus the concrete has lower bleeding, higher strength and enhanced durability. Fly ash fills the gaps within the cement and the pozzolanic reaction forms further cementitious compounds leading to a denser matrix and hence more durable concrete. Cao et al. (2000) reported that replacing 50% of the cement with fly ash, after 28-day moist curing, resulted in the elimination of large pores (>100nm) and halved the total pore volume in the concrete. Another study showed that the inclusion of 30% fly ash significantly reduced the percentage of macro-pores (>50nm) (by 62.5%) and increased the percentage of meso-pores (range of <15nm to 50nm), in addition the total porosity decreased from 13.03% to 11.77% (Megat Johari et al., 2011). In their paper, Shafiq & Cabrera (2004) reported that the total porosity of a mix with 50% fly ash, after 28 days moist-curing, is lower than that of the Portland cement mix. This is contradicted in another paper which reported that, after 28 days moist-curing, the percentage of larger pores in mix with 50% fly ash was higher than the reference Portland cement mix, hence the total porosity of the reference mix was lower, however the argument put forward for this was that, due to the slower hydration reaction of fly ash mixes, the beneficial effects of fly ash was not reflected after only 28 days of moist-curing and longer period was of curing was needed (Ramezanianpour & Malhotra, 1995).

This denser matrix also helps in limiting the amount of harmful chemicals entering the concrete. Elahi et al. (2010) showed that the chloride diffusion coefficient of the concrete decreased from 3.1×10^{-12} m^2/s to 1.35×10^{-12} m^2/s and 1.5×10^{-12} m^2/s with fly ash addition of 20 and 40% respectively. This is also mirrored by the results obtained by Zhu & Bartos (2003) where the chloride migration coefficient for self-compacting concrete with fly ash was lower (5.9×10^{-12} m^2/s) compared to the reference Portland cement mix (17.3×10^{-12} m^2/s). A similar trend was also observed by Dhir at al. (1993). The RCP test results (charge passed) for self-compacting concrete (water/binder ratio 0.33) with fly ash replacement levels of 0, 15, 25 and 35% were 1250, 480, 300 and 150 coulombs (Uysal et al., 2012), which is in line with the migration coefficient results, all indicating that the addition of fly ash improves resistance to chloride ingress. A similar trend in the RCP results was also obtained by Boğa & Topçu (2012).

Elahi et al. (2010) also reported that relative sorptivity coefficient of concrete with 20 and 40% fly ash, after 91 days, was 73 and 116% compared to the reference Portland cement mix and that sorptivity decreased with age. However Gopalan (1996) reported that, after 91 days, the concrete mix with 20 and 40% fly ash had sorptivity coefficients of 9 and 5.9 mm/hr$^{1/2}$ after 91 days compared to 10.1 mm/hr$^{1/2}$ for the Portland cement concrete mix.

When considering alkali-silica reaction (ASR) fly ash (Class F) reduces the overall alkalinity of the pore solution and for this reason the calcium-silicate hydrates formed due to the pozzolanic reaction are low in calcium and so have high alkali binding capacity (Shehata et al., 1999). Thomas et al. (2011) showed that for exposure times of 16 to 18 years, the replacement of 25 and 40% fly ash was successful in significantly reducing expansion and cracking and they also reported that there was no evidence of alkali contribution from the fly ash. Results from various other studies are in agreement with the above (Sibbick & Page, 1995; Shayan et al., 1996; Lindgård et al., 2012). The UKQAA (2012) mentions that for significant reduction in risk of ASR the fly ash replacement level must be at least 25%.

As with ggbs, fly ash consumes the calcium hydroxide produced from Portland cement hydration hence the amount of calcium hydroxide is reduced within the cement matrix leading to an increased sulphate resistance. Uysal & Sumer (2011) studied the compressive strength loss of two sets of self-compacting concrete specimens, one immersed in 10% magnesium sulphate solution and another immersed in 10% sodium sulphate solution. After 400 days exposure in magnesium sulphate solution, the loss in compressive strength for the Portland cement mix was 13% whereas mixes with 15, 25 and 35% fly ash replacement had losses of 10, 8.5 and 6.5% respectively. The compressive strength losses were lower for the specimens immersed in sodium sulphate solution with the Portland cement mix being 9.5% and the fly ash mixes standing at 7, 4 and 3% respectively. In both cases the mix with 35% fly ash replacement performed better than others having the lowest strength loss. In another study (Atahan & Dikme, 2011), the expansion of mortar mixes made with sulphate contaminated sand (2% water soluble sulphate by weight) immersed in calcium hydroxide solution was recorded. The expansion of the reference Portland cement mix, after 12 months immersion period, was about 0.55% compared to 0.2, 0.12 and 0.08% for mixes containing 15, 30 and 45% fly ash replacement.

2.4.2.5 High-volume fly ash concrete

In the last two decades there has been considerable work done looking at increasing the replacement level of fly ash in concrete above the typical levels (up to 40%) for both technical and environmental reasons. A study on High-volume fly ash (HVFA) concrete was initiated by the Canadian Centre for Mineral and Energy Technology (CANMET) in the 1985. This is defined as a concrete in which at least 50% (by mass) of the Portland cement is replaced with Class F fly ash. The aim of the study was to develop an HVFA concrete with adequate early-age strength and workability, low heat of hydration and high long-term strength (Malhotra & Mehta, 2008). A low water/binder ratio (<0.40) is necessary for achieving high early-age strength and, due to the low water content of HVFA concrete, the use of superplasticising admixture is needed to achieve the required consistence. In a recent study self-compacting concrete with replacement levels of up to 80% (water/binder ratio 0.35) was found to be possible (Hannesson et al., 2012). The SCC mix with 80% fly ash replacement, at 28 and 56 days, achieved compressive strengths of 32 and 45MPa respectively. Other studies have also demonstrated the possibility of producing concrete with fly ash replacement levels ranging from 50 to 70% with adequate mechanical properties (Poon et al., 2000; Cao et al., 2000; Bilodeau & Malhotra, 2000; Bilodeau et al., 1994; Jiang & Guan, 1999; Reiner & Rens, 2006; Atiş, 2003).

Due to the low cement content of HVFA concrete, insufficient $Ca(OH)_2$ is produced from the Portland cement hydration reaction to react with all the fly ash, hence a significant volume of the fly ash remains unreacted and is evenly distributed within the dense matrix (Lam et al., 2000; Zhang, 1995). The unreacted fly ash particles act as micro-aggregates in the concrete matrix which help in restricting shrinkage and creep (Zhang, 1995). This could be the reason for the superior durability properties, such as shrinkage, sulphate resistance and chloride penetration resistance, of HVFA concrete compared to concrete without fly ash (Atiş, 2003; Dinakar et al., 2008).

The use of HVFA concrete is an attractive option for the concrete industry for both environmental and sustainability reasons, in addition to the low initial material costs and excellent durability properties. HVFA concrete has been utilised mainly in the USA and Canada for various applications such as highway construction, soil stabilisation and embankments. Also the number of applications is increasing as the demand for more environmentally friendly concrete increases and in addition the landfill space is limited and expensive (Malhotra & Mehta, 2008; Mehta, 1999).

2.4.2.6 Improving the reactivity of fly ash

As discussed above, and as with ggbs, using fly ash as a partial replacement of Portland cement leads to lower strength and slow strength gain at early ages because of the slow rate of the pozzolanic reaction between the silica in fly ash and $Ca(OH)_2$. It is important to find methods of improving the reactivity of fly ash as that will subsequently lead to use of higher replacement levels; this is especially important in HVFA concrete where a significant amount of the fly ash remains unreacted. Three methods are commonly used to improve the reactivity of fly ash (section 2.4), these are briefly explained below.

Mechanical treatment: Chindaprasirt et al. (2005) studied the effect of fly ash fineness on compressive strength and pore size of blended cement pastes. They utilised two types of fly ash with different size ranges, a coarse one with median particle size of 19.1µm and a finer one with median particle size of 6.4µm. They found that the cement paste, with 40% fly ash replacement level and water/binder ratio of 0.35, made of the finer fly ash had a higher 90-day compressive strength (78.5MPa) compared to that made with the coarser fly ash (61.4MPa). In the same study, it was also reported that both the pore size distribution and the average pore diameter of the paste decreased with increasing fly ash fineness. In another study it was reported that the rate of both the hydration reaction and pozzolanic reaction increased with increasing fly ash fineness which can explain the increase in compressive strength reported by the previous study (Chindaprasirt et al., 2007). Similar conclusions were drawn by other studies (Bentz et al., 2011; Lawrence et al., 2005; Karim et al., 2011; Payá et al., 1995; Payá et al., 1996; Payá et al., 1997). Chindaprasirt et al. (2007) noticed that the chloride penetration depth, by partial immersion in 3% NaCl solution, in the concrete was reduced by the use of finer fly ash. A similar trend was observed with the RCP test, with lower total charge passing for mixes with finer fly ash which could be due to the denser matrix of the paste providing improved resistance to chemical penetration.

Thermal treatment: Payá et al. (2000) looked at the strength development of ground fly ash in mortar mixes cured at different temperatures. Increasing the curing temperature led to an increase in early-age compressive strength. Mortar mixes with 30% fly ash replacement cured at 20, 40, 60 and 80°C achieved 3-day compressive strengths of 15.9, 24.5, 28.9 and 32.2 MPa respectively. Though all these strengths were lower compared to that of the reference Portland cement mix cured at those temperatures, this is indicative that increase in temperature, as a catalyst, increases the rate of both the hydration reaction and subsequently the rate of the pozzolanic reaction of fly ash which has been reported by other studies (Hanehara et al., 2001; Narmluk & Nawa, 2011). However a different trend was observed with the 28-day strength where the strengths of the mortar mixes were 34.4, 47.3, 37.2 and 31.9 MPa respectively. Increasing the curing temperature from 20 to 40°C led to an increase in the 28-day compressive strength however further increase of curing temperature to 60 and 80°C led to a reduction in the 28-day compressive strength. A reason for this could be that due to the increased rate of reaction, the cementitious hydrates are rapidly and less uniformly formed leading to a weaker matrix hence lower compressive strength. Also curing at such high temperatures could result in micro-cracking in the concrete matrix reducing overall strength. Results obtained by Narmluk & Nawa (2011) show that for a paste mix with 50% fly ash replacement (water/binder ratio 0.25) the degree of hydration reaches levels above 0.8 (at 1000 hours) when cured at 20 and 35°C whereas for the paste cured at a higher temperature of 50°C, the degree of hydration seems to plateau at 0.8 after 100 hours.

Chemical treatment: As with ggbs, the reaction rate of fly ash can be improved by increasing the alkalinity of the pore solution (refer section 2.4.1.5). Over the past 20 years, with the goal of achieving higher replacement levels and the introduction to HVFA concrete, interest in looking at improving fly ash reactivity through chemical activation has increased. In their study, Saraswathy et al. (2003) concluded that the use of chemically activated fly ash yielded better results compared to using mechanically and thermally activated fly ash. Various chemicals have been used as activators such as high concentrations of $Ca(OH)_2$ (Ma et al., 1995; Ma & Brown, 1997), NaOH (Katz, 1998; Criado et al., 2012; Somna et al., 2011), $CaSO_4$ (Ma & Brown, 1997; Ma et al., 1995; Poon et al., 2001), Na_2SO_4 (Lee et al., 2003; Criado et al., 2010), Na_2CO_3 (Xie & Xi, 2001), KOH (Palomo et al., 1999) and Na_2SiO_3 (Palomo et al., 1999; Komljenović et al., 2010; Shi et al., 2012). The addition of these chemical activators leads to an increased rate of pozzolanic reaction resulting in higher compressive strengths at early ages. In their study Fernández-Jiménez et al. (2006) compared two concrete mixes, one made with ordinary Portland cement and one made with alkali-activated fly ash (the activator used was a mixture of 85% NaOH + 15% Na_2SiO_3). The mechanical strength and shrinkage properties of concrete mixes were compared and their results show that the rapid strength gain of alkali-activated fly ash concrete of about 50MPa at 1 day compared to 10MPa for the Portland cement mix. However it is worth noting that the alkali-activated fly ash mix obtained its maximum strength at 1-day and the strength rise thereafter was very slow (58MPa at 28 days) whereas the ordinary Portland cement mix had more noticeable strength gain up to 28 days (30MPa) as they gain almost 90% of their maximum strength only after 28 days. The shrinkage properties of the alkali-activated fly ash mix was better that the reference Portland cement mix, where at 90 days, the values were 0.01 and 0.09% respectively. As with alkali-activated slag (section 2.4.1.5), the performance of mixes made with alkali-activated fly ash depend on many factors such as the nature of the activator (Fernández-Jiménez & Palomo, 2005; Komljenović et al., 2010), activator concentration (dosage) (Guo et al., 2010; de Vargas et al., 2011; Criado et al., 2007) and curing temperature (Palomo et al., 2004; Guo et al., 2010).

In addition to the factors mentioned above, there are still concerns and problems which need to be addressed with regards to concrete made with alkali-activated cement such as larger drying shrinkage and higher carbonation rate compared to Portland cement concrete (Shi et al., 2006). Also there is little literature available about the effects of chemical admixtures on the properties of concrete made with alkali-activated cements as most chemical admixtures currently available on the market are mainly for Portland cement-based mixes and do not seem to work well with alkali-activated cement concrete (Collins & Sanjayan, 1999; Puertas et al., 2003; Shi et al., 2006; Bilim et al., 2013).

2.4.3 Limestone powder

Limestone is a very strong rock and it is formed in marine environments from the precipitation of calcium carbonate ($CaCO_3$). There are large amounts of limestone (chalk) cliffs in the coastal regions of England. Limestone, in addition to being one of the raw material for the production of Portland cement, has been utilised within the construction industry in various ways. Limestone rocks have been used as coarse aggregate in concrete (Uysal, 2012) and as building blocks in construction projects. Crushed limestone sand has also been used, in countries such as Spain, France and Argentina, as part of the fine aggregate due to the lack of availability of natural sand (Li et al., 2009; Menadi et al., 2009; Aquino et al., 2010). Limestone powder, essentially $CaCO_3$ ground to a particular fineness, has also been used as a filler material partially replacing the Portland cement in concrete. The standard BS EN 197-1 (2011) identifies four types of Portland-limestone cement two of which contain 6-20% limestone (CEM II/A-L and CEM II/A-LL) and the other two containing 21-35% limestone (CEM II/B-L and CEM II/B-LL). The requirements for limestone in the standard are as follows:

- $CaCO_3$ content $\geq$ 75% by mass
- Clay content $\leq$ 1.20g/100g
- Total Organic Carbon (TOC) $\leq$ 0.20% for LL limestone and $\leq$ 0.50% for L limestone

Addition of limestone powder can be done by either: pre-blended or factory-blended done by inter-grinding the limestone directly with the clinker in the cement production plant producing CEM II Portland-limestone cement; or by directly adding limestone powder to CEM I Portland cement within the mixer (within-mixer) when producing concrete in the batching plant. Due to the fact that limestone is weaker than clinker, after the grinding process, it ends up being finer than the ground clinker hence factory-blended Portland-limestone cements (PLCs) are generally finer than pure Portland cements and have a smaller median particle size (Higgins, 2009). Portland-limestone cements are produced at numerous plants across the UK, however these cements have not been used to any great extent within the UK compared to Europe where they accounted for more than 24% of all cements in 2000 (approximately 40 million tonnes) (Price, 2004).

There have been various studies looking at the properties and behaviour of concrete containing limestone powder. Limestone powder is currently classified as a Type I addition i.e. nearly inert which indicates that it plays no role in the hydration reaction chemically; hence its effects are of a physical nature. However studies have shown that the calcium carbonate ($CaCO_3$) in limestone powder does in fact react with the tri-calcium aluminate (C_3A) in the cement forming calcium carboaluminate hydrates on the surface of the C_3A grains which in turn modifies and accelerates the cement hydration reaction and the formation of the calcium-silicate hydrates (C-S-H) i.e. the effects are therefore not solely physical (Bonavetti et al., 2000; Bonavetti et al., 2001; Kakali et al., 2000; Yang et al., 2011). It has been generally accepted across the literature that the physical effects due to the addition of limestone powder are the dilution effect, filler effect and heterogeneous nucleation (Tsivilis et al., 1999; Tsivilis et al., 2003; Voglis et al., 2005; Ramezanianpour et al., 2009; Kadri et al., 2010; Ingram & Daugherty, 1991).

Increase in the percentage replacement of limestone powder means a decrease in the amount of Portland cement within the concrete (dilution effect) and consequently an increase in the effective water/cement ratio hence leading to a decrease in the compressive strength of the concrete. The addition of limestone powder, due to it being finer than Portland cement, changes the initial porosity of the mix (filler effect) increasing the consistence of the concrete or in other sense decreasing the amount of water required to maintain constant consistence. Finally the heterogeneous nucleation occurs because limestone particles act as sites of nucleation and growth for the hydrating cement increasing the surface area available for the hydrates and consequently having a catalyst effect and accelerating the rate of the hydration reaction. The impact of limestone powder on the various properties of the concrete, due to the filler effect and the heterogeneous nucleation, is very much dependent on the fineness of limestone powder used with the finer powder having a greater effect. In this section the effects of limestone powder as a partial replacement of Portland cement, on both the fresh and hardened properties of the concrete, are discussed.

2.4.3.1 Fresh properties

Limestone powder is generally finer than Portland cement hence combining these two will result in a binder which has a greater overall fineness and better particle packing than pure Portland cement. Portland-limestone cement, despite its larger surface area (SSA), has a lower paste water demand, i.e. increased consistence for the same water content, compared to pure Portland cement (Tsivilis et al., 1999; Voglis et al., 2005; Hawkins et al., 2003). Tsivilis et al. (1999) showed that limestone replacement levels of 10, 20 and 35% reduced the mix water demand from 26% for the reference Portland cement mix to 25.4%, 23.5% and 22.9% respectively. Other studies also noticed a similar trend (Lv et al., 2011; Wang et al., 2011; Yang et al., 2011). Ramezanianpour et al. (2009) showed that a concrete mix, water/binder ratio of 0.37, with 10% limestone powder replacement level has a slump of 90mm compared to 80mm for the reference Portland cement mix. Wang et al. (2011) showed that the reduction in paste water demand was greater as the fineness of the limestone powder increased. For a 10% replacement level, limestone powders having SSA of 416, 841 and 1243m^2/kg gave slump values of 180, 185 and 195 respectively compared to a slump of 170mm for the pure Portland cement mix. However the results of Gesoğlu et al. (2012) seem to contradict this as the slump flow diameter of the SCC mixes with 10 and 20% limestone powder replacement was lower (650 and 660mm respectively) than that obtained for the Portland cement control mix (700mm).

2.4.3.2 Early age properties

As mentioned above, with the addition of limestone powder, due to the heterogeneous nucleation effect, the rate of hydration reaction is increased resulting in the reduction in both the initial and final setting time of the mix. Mounanga et al. (2011) mentions that, with a limestone replacement of 25% and 50%, the final setting time reduces from 537min to 421min and 413min respectively. Other studies also show similar trends (Tsivilis et al., 1999; Rahhal et al., 2012; Lv et al., 2011). The reduction in the initial and final setting time is greater with increased percentage replacement of limestone powder and also with increased specific surface area (fineness) of the limestone powder (Lv et al., 2011).

As for the heat of hydration, the maximum intensity of heat output decreases with the increase in limestone powder content since the cement content available to hydrate is reduced. With increased limestone powder content the amount of hydrates formed is reduced leading to less heat output (Figure 2-7). It is worth mentioning that the time taken to reach maximum heat flow reduces with increase in limestone powder which could be attributed to the catalyst effect of limestone powder accelerating the rate of the cement hydration reaction. Referring to Figure 2-7, a limestone powder replacement of 25% and 50%, the time to reach maximum heat output reduced from 498min to 484min and 391min respectively (Mounanga et al., 2011).

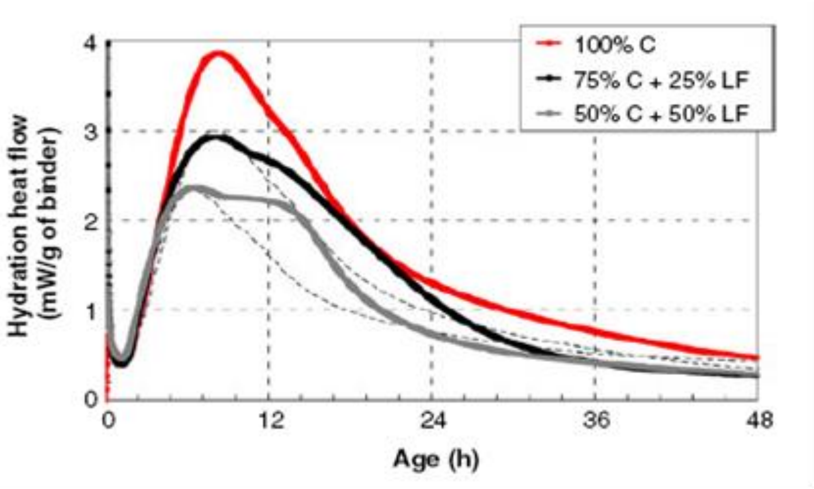


Figure 2-7 Hydration heat output rate for limestone powder concrete (Mounanga et al., 2011)

2.4.3.3 Strength

As mentioned in Section 2.4.3, the heterogeneous nucleation effect, due to the addition of limestone powder, increases the rate of hydration reaction resulting in the concrete having a slightly higher compressive strength at early ages (up to 7 days) (Tsivilis et al., 1999; Ghrici et al., 2007; Ramezanianpour et al., 2009). Due to the dilution effect, the long-term strength of the concrete incorporating limestone powder as a partial replacement of Portland cement will still be lower relative to concrete where Portland cement is used as the sole binder. The results from Tsivilis et al. (1999) show that the 7-day compressive strength of the concrete mix, up to 20% limestone powder replacement (by inter-grinding), was similar or higher than that of the reference Portland cement mix. The strength of the Portland-limestone concrete, at 28 days, was lower than the reference Portland cement mix except for the mix containing 5% limestone powder replacement where the strength was about 2MPa higher. Ghrici et al. (2007) and Ramezanianpour et al. (2009) also show similar results in their studies i.e. slightly higher early strength with a drop in strength at later ages for Portland-limestone concrete. Tsivilis et al. (1999) also showed that by inter-grinding the clinker and limestone for a longer period of time produces a finer product resulting in an increased rate of hydration reaction. Taking the same mix with 20% limestone powder replacement, the mix where the clinker and limestone had been inter-ground for 38 minutes had 28-day strength of 44MPa whereas in the mix where the inter-grinding time was 60 minutes, the strength was 47MPa at the same age. Wang et al. (2011) also looked at the effect of limestone fineness on the compressive strength of concrete and concluded that for the same replacement level (up to 15%), using a finer limestone powder leads to improvement in the compressive strength of the concrete both at 7 and 28 days. Considering the 28-day strength, the reference Portland cement mix obtained a strength of 77.2MPa, and the mixes with 15% replacement incorporating limestone powder with fineness (SSA) of 416, 841 and 1243m^2/kg obtained compressive strengths of 74.5, 77.3 and 79.2MPa respectively. Lv et al. (2011) conducted similar tests with a higher range of limestone replacement levels (up to 35%) and concluded that the increase in fineness of the limestone powder is favourable for the development of compressive strength up to 20% replacement level. Hence it can be said that in terms of the powder properties, the fineness or particle size distribution of limestone powder is a key property affecting the performance of the Portland-limestone cement. However it is important to note that for a particular replacement level, it might not necessarily be the case that a higher fineness of limestone powder would increase the compressive strength hence it is necessary to obtain the optimum particle size distribution which would yield the most favourable results.

Ghrici et al. (2007) showed that the flexural strength of the concrete decreases with an increase in limestone replacement i.e. a concrete with no limestone replacement and one with 20% replacement, at 28 days, had flexural strengths of 8.9 and 7.6 MPa respectively, which is expected as the flexural strength of concrete is proportional to the compressive strength. In their study, the ratio between flexural strength and compressive strength remained at about 0.18- 0.19 for all mixes tested.

2.4.3.4 Durability properties

According to Pipilikaki & Beazi-Katsioti (2009), the use of limestone powder in blended cements changes the pore structure of the hardened cement paste. When the maximum allowable amount (i.e. 35%) is used in blended cements, the capillary pore size increases from 20nm to 40nm however it reduces the threshold diameter, the largest pore size which is structurally continuous, of the paste and provides a more uniform pore size distribution. The reduction in the threshold diameter makes it more difficult for chemicals to enter the hardened cement paste, and the increase in capillary pore size and the more uniform pore distribution allows the chemicals to travel around easier within the hardened cement (Pipilikaki & Beazi-Katsioti, 2009). Furthermore, the resistance to freezing and thawing and salt decay increases which could be attributed to the reduced threshold diameter of the paste better preventing chemicals entering the hardened cement.

Ramezanianpour et al. (2009) studied the effect of limestone powder replacement on the chloride ion penetration resistance of concrete. They conducted the rapid chloride penetration (RCP) test in accordance with ASTM C1202 (2007), on various Portland-limestone concrete mixes with different levels of limestone powder replacement. The results are illustrated in Figure 2-8. It can be noticed that the charge passed, at 10% limestone powder replacement, was lower than the reference mix but increases at higher replacement levels. This is also mirrored in Uysal et al. (2012) where they tested SCC mixes with water/binder ratio 0.33; however Gesoğlu et al. (2012) tested SCC mixes with water/binder ratio of 0.35 and obtained a reduction in the charge passed for replacement levels of 5, 10 and 20%. Also the charge passed is reduced with longer curing period and also by reducing the water/binder ratio, both of which result in the formation of a denser matrix improving the chloride penetration resistance of the concrete.

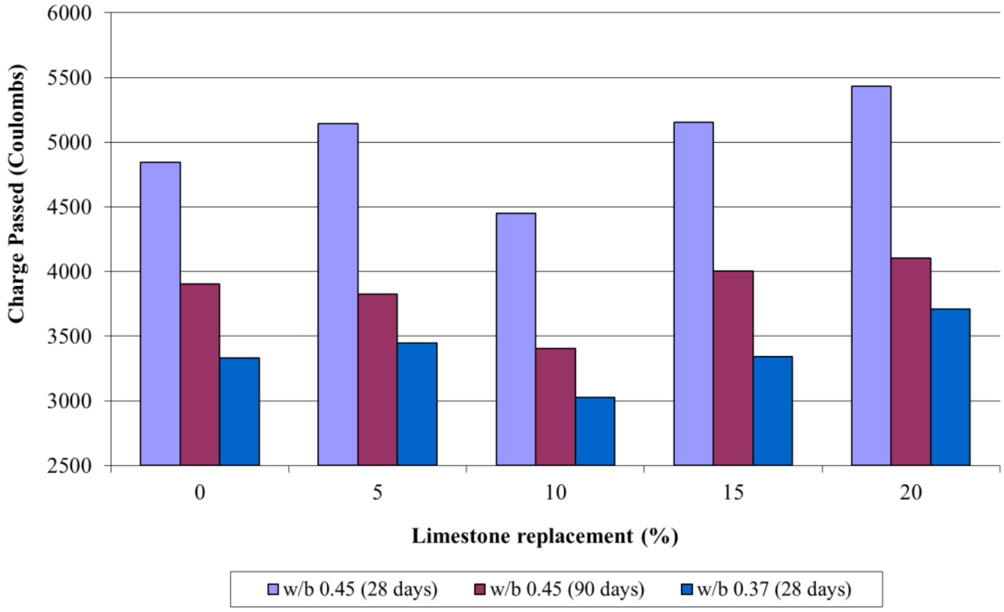


Figure 2-8 Effect of limestone replacement on RCP test results (Ramezanianpour et al., 2009)

Bonavetti et al. (2000) reported that, when immersed in 3% NaCl solution for 45 days, concrete mixes, cured under water at 20°C, containing 10 and 20% limestone replacement resulted in an increase of the chloride penetration depth from 7mm to 10mm and 15mm respectively. They also conducted tests on another set of mixes, cured in air, where the results show that, for all mixes, the chloride penetration depth is higher compared to water-cured mixes which could be due to the formation of a less dense matrix as lack of availability of water did not allow full hydration to take place. The inclusion of 10 and 20% limestone powder in this case resulted in a reduction in penetration depth from 30mm to 17 and 20mm respectively indicating that the chloride penetration depth is also influenced by the curing regime (Bonavetti et al., 2000). Ghrici et al. (2007) also showed that the penetration of chloride ions increases in concrete containing 15% limestone powder replacement. Dhir et al. (2007) used an accelerated test method to obtain the chloride diffusion coefficients for concrete mixes with different limestone replacement levels and water/cement ratios. The accelerated test method, explained in Dhir et al. (1990), involved placing concrete slices (100mm in diameter and 25mm thick) in a two-compartment cell containing a chloride solution, applying a small potential difference (7.5 Volts) across to accelerate the transport of chloride ions through the concrete and finally calculating the chloride diffusion coefficient using Fick's First Law of Diffusion. The results of the tests are illustrated in Figure 2-9.

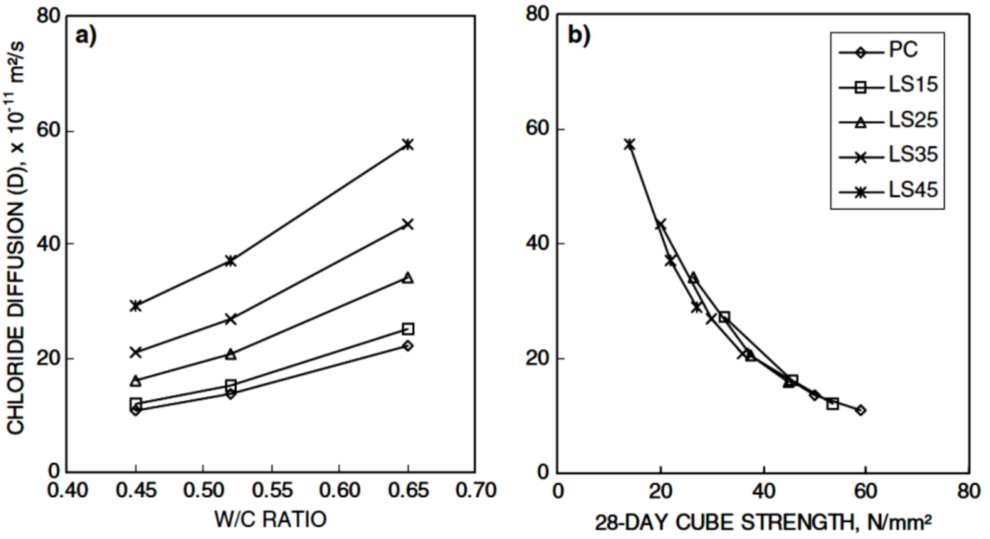


Figure 2-9 Relationship between chloride diffusion and (a) w/c ratio and (b) 28-day cube strength of concrete with limestone powder addition (Dhir et al., 2007)

As it can be noticed on Figure 2-9 (a), the chloride diffusion coefficient decreases as the water/cement ratio of the concrete decreases which is in agreement with the conclusion of Ramezanianpour et al. (2009), that concrete mixes with lower water/cement ratio have better chloride penetration resistance. Dhir at al. (2007) also shows that the addition of limestone powder seems to decrease the chloride resistance of the concrete, as illustrated in Figure 2-9 (a). The differences in the chloride diffusion for the mix with 15% limestone replacement (LS15) compared to the reference mix without limestone powder (PC) were relatively small and seem to decrease with lower water/cement ratios. The general consensus within the literature seems to be the chloride resistance of the concrete is worsened with the addition of limestone powder. Accounting for the fact that the addition of limestone powder leads to a decrease in compressive strength, Dhir et al. (2007) plotted the chloride diffusion coefficient against the cube compressive strength of the mix, illustrated in Figure 2-9 (b), where, for a given 28-day strength, there seems to be little or no difference between the concrete mixes with and without limestone powder. Hence it could be said that two mixes with similar 28-day compressive strength, with or without limestone powder, would have similar or comparable chloride resistance.

Looking at the effect of limestone powder on the sorptivity coefficient of the concrete, Ramezanianpour et al. (2009) showed that the sorptivity coefficient of the concrete increases with increasing limestone replacement, decreases with the reduction in water/binder ratio (Figure 2-10) and with longer curing periods similar to the trends observed with the chloride resistance of concrete. At water/binder ratios of 0.45 and 0.55, the sorptivity coefficients increased with increasing limestone powder replacement however at lower water/binder ratio (0.37), the mix with 10% limestone replacement had the same sorptivity coefficient as the reference PC mix.

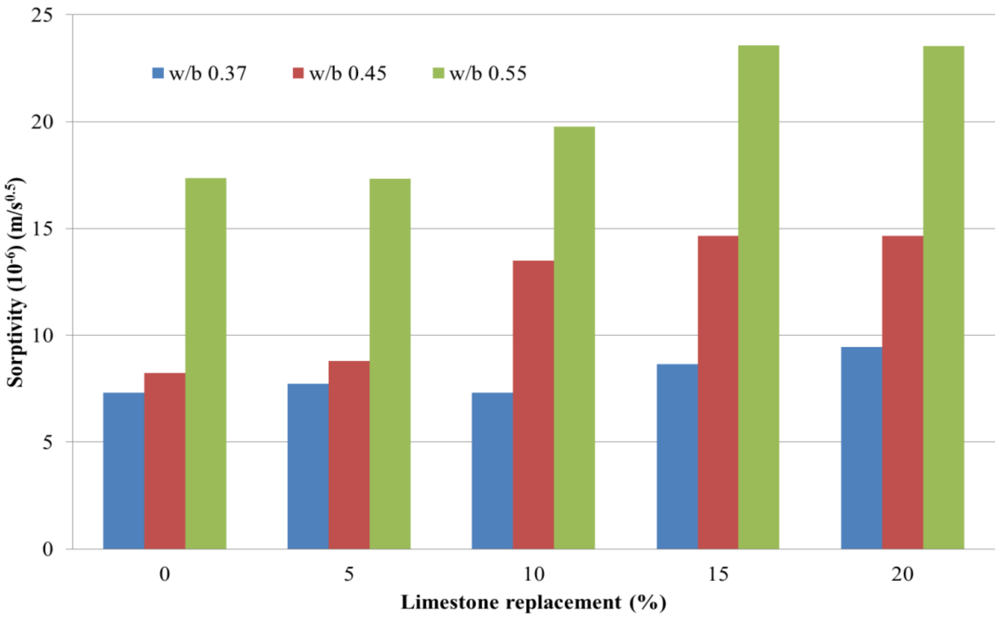


Figure 2-10 Sorptivity coefficients (28 days) for concrete with different limestone powder replacement levels (Ramezanianpour et al., 2009)

Ghrici et al. (2007) observed that the incorporation of 15% limestone powder as a partial cement replacement, at both water/binder ratio of 0.6 and 0.4, decreased the sorptivity coefficients at 28 and 90 days, contradicting the trend observed by Ramezanianpour et al. (2009). This was mirrored by Tsivilis et al. (2003) where increasing limestone powder replacement (water/binder ratio 0.7) lowered the sorptivity coefficient of the mix from 0.237 for the control PC mix to 0.220mm/min$^{0.5}$ for 20% replacement level.

Dhir et al. (2007) studied the effect of limestone powder addition on the carbonation of the concrete using two test environments; in the first test environment (CEN environment), the specimens were exposed to 0.035% CO_2 at 20°C and 65% relative humidity for 365 days and in the second the specimens were stored in an enriched 4% CO_2 environment (accelerated environment) at 20°C and 65% relative humidity for 20 weeks. They observed that the addition of limestone powder led to an increase in the carbonation depth in both cases. Their result is illustrated in Figure 2-11. The carbonation resistance, as with the chloride resistance, increased with lower water/binder ratios and longer curing periods. Dhir at al. (2007) also plotted the carbonation depth versus the 28-day cube compressive strength for all the mixes tested, shown in Figure 2-11 (b), and as with the chloride diffusion coefficient test results (Figure 2-9), this indicated that concrete mixes produced with the same 28-day compressive strength would have similar or comparable carbonation resistance regardless of whether the mix contains any additions. Collepardi et al. (2004) also showed that substitution of 15 or 25% of the Portland cement by limestone powder, fly ash or slag led to an increase in carbonation rate when concrete was compared at equal water/binder ratio, but that the rate was comparable for concretes of equal strengths. Hence the conclusion from these studies is that for a given degree of moist curing and exposure conditions, the rate of carbonation is a function of the concrete strength and seems to be independent of the type of binder used.

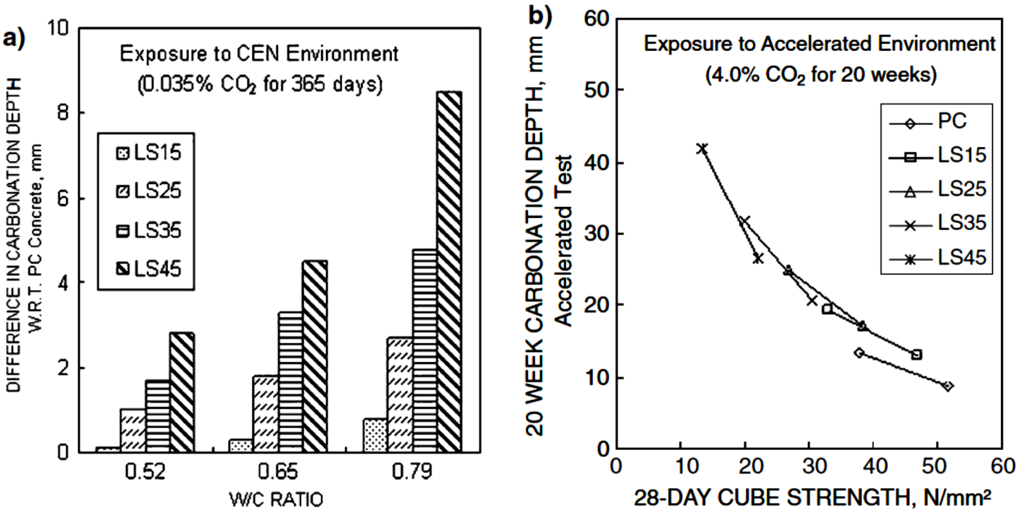


Figure 2-11 Comparison of carbonation resistance at equivalent (a) w/c ratio (CEN environment) and (b) 28-day cube strength (accelerated environment) (Dhir et al., 2007)

The paper by Tsivilis et al. (2002) reported that the addition of limestone powder shows no carbonation after exposure times of 9 and 12 months, compared to a carbonation depth of 3mm and 5mm in Portland cement concrete respectively, contradictory to the findings of Dhir et al. (2007) and Collepardi et al. (2004). Also mentioned in the paper is that there is a clear decrease of corrosion in limestone concrete specimens and also the mass loss of rebars is less than that of Portland cement concrete after a 12 months of immersion in a 3% by weight NaCl solution. The mass loss of rebars decreased from 1.1 mg/cm^2 for the PC mix down to 0.35 mg/cm^2 for mix with 20% limestone replacement after 12 months immersion in the

NaCl solution. Ramezanianpour et al. (2009) mentioned that the corrosion-resisting performance of the concrete is influenced by its electrical resistivity, the higher the electrical resistivity the better the corrosion resistance of the concrete. It went on to show that the electrical resistivity of concrete decreases due to the addition of limestone powder hence the corrosion resistance of the concrete is reduced, mirroring the conclusions of Dhir et al. (2007) and Collepardi et al. (2004).

Hobbs (1983) looked at the effect of limestone powder on alkali-silica reaction (ASR) in mortars and reported that the use of 5% limestone powder, in mortar bars made with high-alkali cement, slightly extended the time to cracking but did not eliminate it. Thomas et al. (2010) conducted three different tests, two accelerated tests, one on mortar bars and the other on concrete prisms (AMBT and ACPT respectively), and one long-term test on concrete prisms (CPT). Two sets of mixes were tested, one made with Portland cement and the other with Portland-limestone cement, to study the effect of limestone powder addition, if any, on ASR. The expansion results are illustrated in Figure 2-12. It can be seen that there is no consistent difference in the expansion values of specimens made with Portland cement and those made with Portland-limestone cement. One would expect that the addition of limestone powder, due to the dilution effect, would reduce the overall alkalinity of the pore solution hence reducing the risk of ASR damage.

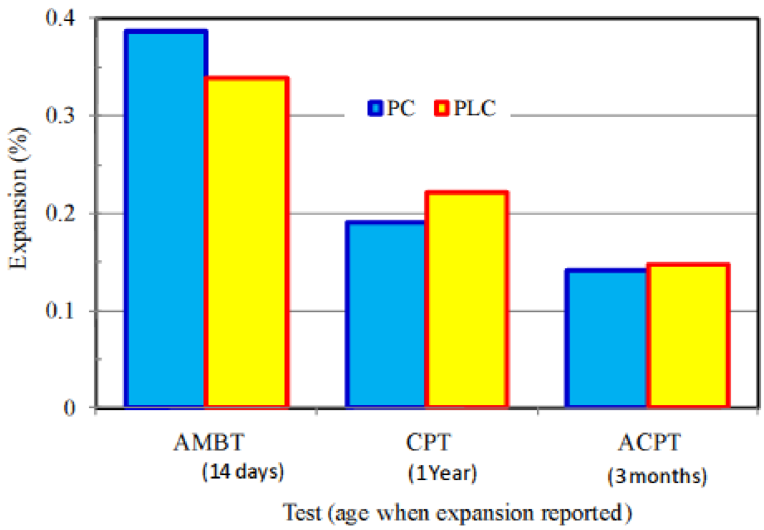


Figure 2-12 Effect of Portland-limestone cement on ASR expansion of mortar and concrete (Thomas et al., 2010)

There have been inconsistencies within the literature of whether limestone powder improves or worsens the sulphate resistance of the concrete. A comprehensive study was done by Irassar (2009) reviewing the work done over the years regarding sulphate attack on cementitious materials containing limestone powder. It concluded that the addition of limestone powder at low levels (<10%) has no significant effect on sulphate resistance of the concrete however higher replacement levels (>15%) lowers the resistance. In addition it is mentioned that the sulphate resistance of Portland-limestone cement is more strongly correlated with the tri-calcium aluminate (C_3A) content of the parent cement than the limestone powder replacement level. Higher C_3A contents within the parent cement decrease the sulphate resistance of the concrete, as more mono-sulphoaluminates are present in the hydrated Portland cement matrix which will react with sulphate ions forming ettringite, which is an expansive compound, causing damage to the concrete. Low water/cement ratio and good curing of the concrete could protect the concrete against sulphate attack because of its ability to retard the ingress of harmful chemicals and water movement within the concrete matrix. Many studies, such as the one by Khatri et al. (1997), mention the importance of permeability and the ability for the concrete to resist ingress and water movement in producing a sulphate resistant concrete. Other studies such as Skaropoulou et al. (2009), Tosun et al. (2009) and Pipilikaki et al. (2009) also reflect these conclusions.

2.5 Ternary blended binders

All the studies mentioned above look at binary blends of the powders (Portland cement + secondary/filler powder), however a great amount of research has also been done, over the past two decades, looking at concrete with ternary and quaternary blended binders. The main intentions behind combining different additions were to see whether it is possible to combine the benefits of each addition and, in some cases, to see whether one addition can compensate for the shortcoming of the other. Majority of the studies in this area have looked at the effects of ternary and quaternary binders, with various combinations of Portland cement, fly ash, ggbs and silica fume (a by-product from the production of silicon), on the various properties of concrete (Turk, 2012; Bagheri et al., 2012; Gesoğlu et al., 2009; Codina et al., 2008; Thomas et al., 2007; Pandey et al., 2003; Shehata & Thomas, 2002; Khan et al., 2000; Jones et al., 1997; Domone & Soutsos, 1995). It is well known that the addition of silica fume results in considerable improvements in both mechanical (high early-age strength) and durability properties of the concrete, however it does have some drawbacks such as increased water demand (reduced workability), cost and limited availability (Holland, 2005). As mentioned in sections 2.4.1 and 2.4.2, the incorporation of ggbs and fly ash as additions in concrete leads to reduction in water demand but also low early strengths. Many studies have found that combining small amounts (up to 10%) of silica fume along with ggbs or fly ash (ternary binder) in concrete can improve early strength of the mix compensating for the shortcomings of ggbs and fly ash, and in turn fly ash and ggbs can reduce the mix water demand, compensating for the shortcomings of silica fume. Being able to achieve satisfactory properties with ternary and quaternary blended binders creates greater ground for further reduction of Portland cement in concrete.

As majority of the studies on the use of additions in concrete, over the past 20 years, has been focused on the use of ggbs, fly ash and silica fume in concrete, with limestone powder taking a back seat, there are very few studies looking at the effect of Portland cement, fly ash or ggbs and limestone powder combinations as ternary or even quaternary blended binders, on the various properties of concrete.

(Kawashima et al., 2012; Rizwan & Bier, 2012; Bentz et al., 2012; Wang et al., 2011; Hou et al., 2011; Sato & Beaudoin, 2011; De Weerdt et al., 2011b; De Weerdt et al., 2011; Zhou et al., 2010; Boel et al., 2007). As it can be seen, a great number of studies on ternary blended binders with limestone powder have been done only over the past few years indicating that there is increasing interest in this area of research. A number of earlier studies were done on self-compacting concrete incorporating ternary blended binders with limestone powder; however these studies were more focused on the application of the concrete rather than looking at variations and effects on the fresh, hardened mechanical and durability properties of the concrete (Furuya et al., 1994; Wetzig, 1999; Ohtomo et al., 2001; Jacobs & Hunkeler, 2001; Brameshuber & Uebachs, 2001; Collepardi et al., 2003). In this section the use of ternary blended binders composed of Portland cement, limestone powder and ggbs or fly ash on various concrete properties is discussed.

2.5.1 Ternary binders with limestone powder and ggbs

Over the past decade, a number of studies have been done looking at the effect of ternary blended binders containing limestone powder and ggbs on the various properties of the concrete. In this section results from those studies are presented and discussed.

2.5.1.1 Fresh Properties

As mentioned in sections 2.4.1.1 and 2.4.3.1, the addition of ggbs and limestone powder individually in concrete within binary binder mixes resulted in reduction in the mix water demand hence an increase in the slump value of the mix (tested immediately or shortly after mixing is completed). The addition of 20% ggbs to Portland-limestone cement (18% limestone powder) however resulted in the concrete mix having better slump retention (Menéndez et al., 2002). Referring to Figure 2-13, it can be seen that that the slump value for Portland-limestone concrete (PCL) dropped from 240mm to 200mm after 60min whereas the Portland-limestone concrete with 20% ggbs (PCL+20S) retained its slump at 240mm. Hence it can be said that the addition of ggbs compensates for and further improves the slump retention period of Portland-limestone concrete mix.

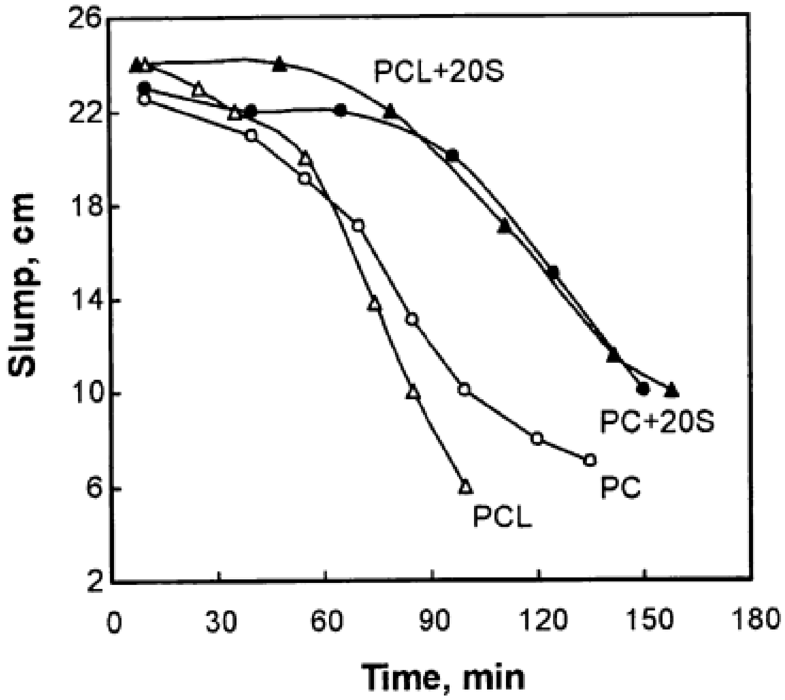


Figure 2-13 Slump value for ternary binder mixes with ggbs and limestone powder (Menéndez et al., 2002)

2.5.1.2 Early age properties

As for the setting time, the mixes having replacement of 8 and 33% of limestone powder both had a final setting time of 525min which is shorter than that of the reference control mix (537min), and the mixes have a 17% limestone replacement had longer final setting time compared to the control mix (Mounanga et al., 2011).

Mounanga et al. (2011) compared binary blend mixes containing 25 and 50% ggbs with ternary blend mixes containing both ggbs and limestone powder. The ternary blend mixes were produced by replacing part of the ggbs with limestone powder, keeping the total cement replacement level constant. The heat of hydration results are shown in Figure 2-14. As the limestone powder content increases, it can be noticed that the time taken to reach peak heat output is reduced, for example it can be seen that for the mix with a 50% ggbs replacement, when substituting 17 and 33% of the ggbs with limestone, the time to peak heat output decreases from 505min to 389 and 371min respectively. In both cases, the peak heat released is higher when a portion of ggbs is replaced with limestone powder. For example, for the concrete with 25% ggbs replacement, the substitution of ggbs with limestone powder caused an increase in the peak heat almost reaching the heat level of the control mix with pure Portland cement. However it should be noted that none of the mixes exceeded that of the control mix. This acceleration effect was also observed with mixes having binary blends of Portland cement and limestone powder (Figure 2-7), as the presence of limestone powder results in a greater surface area for hydration to occur (nucleation effect) resulting in increased rate of hydration reaction. In this case, the increased reaction rate with the addition of limestone powder compensates for the slow reaction rate of ggbs. The heat released by ternary binder mixes is higher than binary binder mixes incorporating ggbs and limestone individually. This effect is greater with increased limestone powder fineness as reported by Sato & Beaudoin (2011) where they showed that the peak heat flow increased and peak heat flow time reduced for mix containing nano-$CaCO_3$ compared with that containing micro-$CaCO_3$.

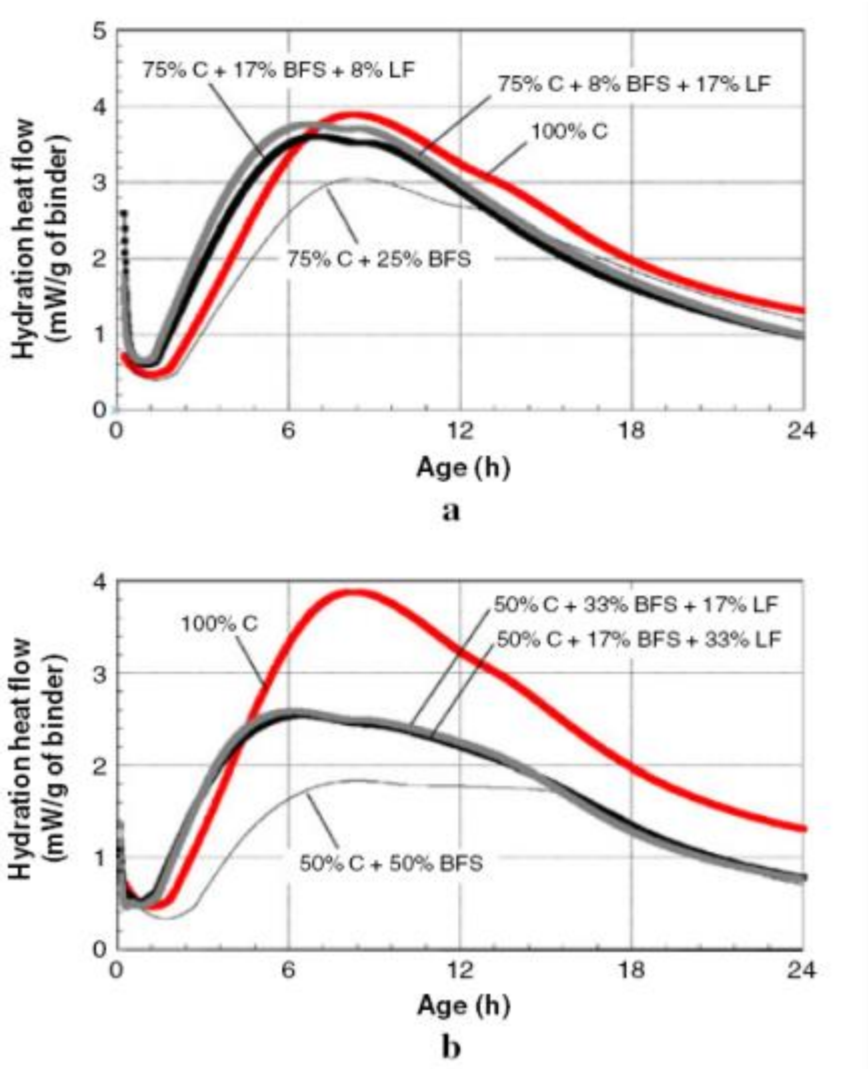
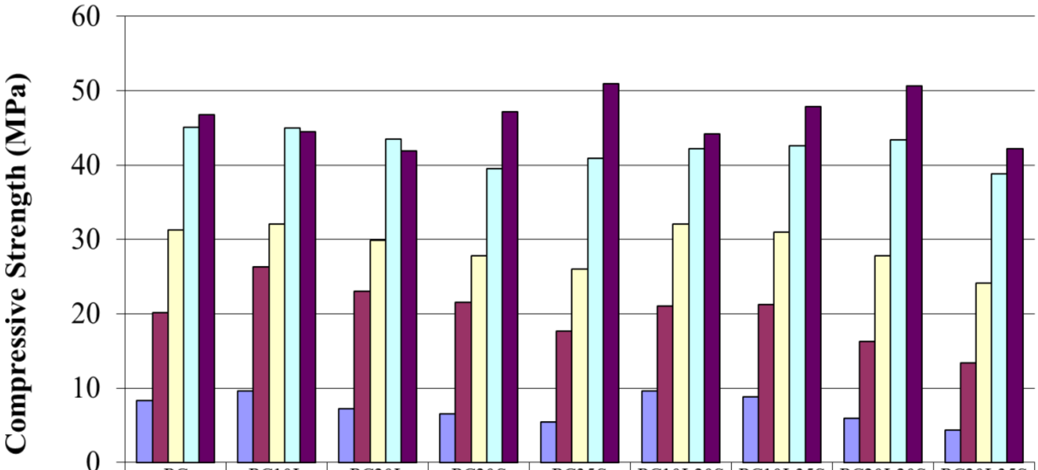


Figure 2-14 Hydration heat output rate for ternary binder mixes with ggbs and limestone powder (Mounanga et al., 2011)

2.5.1.3 Strength

When looking at the heat of hydration curves of ternary binders with ggbs and limestone powder (refer to 2.5.1.1), it was noticed that the presence of limestone increased the peak heat and reduced the time taken to reach peak heat flow indicating increased rate of hydration reaction (primary and secondary) within the paste at early ages. The consequence of this should be visible when looking at the compressive strength of the concrete. Menéndez et al. (2003) examined the strength development of mortar mixes with ternary blended cement incorporating ggbs and limestone and concluded that the combination of these two had a complementary effect. Limestone powder increased the early strength of the cement whereas ggbs improved the later strength. The outcome from this study is illustrated in Figure 2-15.

Looking at mortar mixes PC20S and PC35S (mixes with 20 and 35% ggbs respectively), as expected, we notice that the early strengths are lower than that of the control mix (PC) but soon increases and exceeds the strength of the control mix. Similarly looking at mixes with 10 and 20% limestone powder (PC10L and PC20L respectively), we see that they have higher early strengths compared to the control mix but at later ages the strength of the mixes fall below the control mix due to the dilution effect, again as expected.



	PC	PC10L	PC20L	PC20S	PC35S	PC10L20S	PC10L35S	PC20L20S	PC20L35S
■ 1 Day	8.3	9.6	7.2	6.5	5.4	9.6	8.8	5.9	4.3
■ 3 Day	20.1	26.3	23	21.5	17.7	21	21.2	16.3	13.4
□ 7 Day	31.3	32.1	29.9	27.8	26	32.1	31	27.8	24.1
□ 28 Day	45.1	45	43.5	39.5	40.9	42.2	42.6	43.4	38.8
■ 90 Day	46.8	44.5	41.9	47.2	50.9	44.2	47.9	50.6	42.2

Figure 2-15 Compressive strength of ternary binder mortar with ggbs and limestone powder (Menéndez et al., 2003)

For the ternary binder mixes, comparing mix PC35S with ternary blends PC10L35S and PC20L35S (these two have 10 and 20% limestone replacement in addition to the 35% ggbs), it can be seen that the PC10L35S has a higher early strength compared to PC35S (at 7 days the strength of PC10L35S was 31MPa compared to 26 MPa for PC35S), which is attributed to the increased hydration rate due to the addition of limestone powder (nucleation effect). The strength, at 90 days, of mix

PC10L35S is however slightly less (47.9 MPa) than mix PC35S (50.9 MPa) which could be due to the fact that there is less Portland cement in the mix hence less calcium hydroxide is produced from its hydration for the secondary reaction with ggbs. Looking at mix PC20L35S, it can be seen that the early strength of this mix is, unlike PC10L35S, slightly lower than that of PC35S, which could be attributed to the dilution effect, in addition the long-term strength (90-day) is also lower than the PC10L35S mix which could be due to increased dilution effect and lower Portland cement content. In the latter case, the positive effects (nucleation effect) expected due to the addition of limestone was absent and instead the negative effect (reduction in strength) was greater.

Carrasco et al. (2005) also looked at the strength development of mortar mixes made with ternary blend of limestone and ggbs. Similar to Menéndez et al. (2003), they concluded that combining ggbs and limestone powder has beneficial effects on the strength properties of the concrete mix; but it was necessary to understand the interaction between the two powders and obtain the optimum replacement levels of each giving the best outcome. In their study they produced isoresponse curves for compressive strength of the mixes to highlight the effect and interactions of these two powders and to help obtain the optimum replacement level of each addition. These curves are shown in Figure 2-16. As we can see from the figure, the addition of limestone powder has beneficial effects at early ages whereas at later ages the increase in strength is solely due to the presence of ggbs. For example at 2, 7 and 14 days, a mix with 15% slag has a lower strength than a ternary binder mix with 15% slag and 10% limestone powder, whereas at later ages the addition of limestone powder has a negative effect on strength as there is less Portland cement available to hydrate. A similar conclusion was also drawn by Irassar et al. (2006) in their study where tests were performed on concrete specimens. As expected, similar trends to the compressive strength were observed with the flexural strength of ternary binder mixes by both Carrasco et al. (2005) and Irassar et al. (2006) (Figure 2-17).

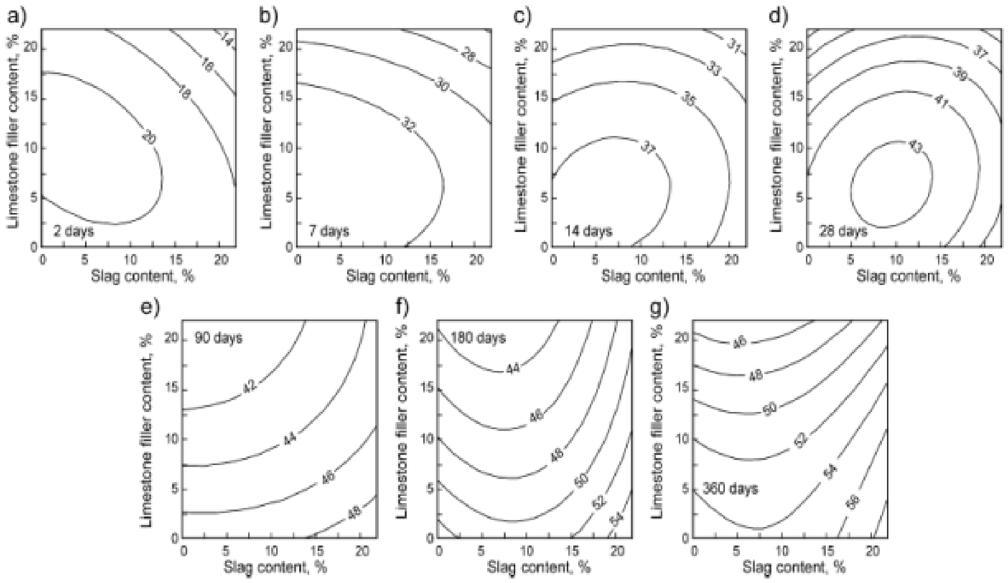


Figure 2-16 Isoresponse curves for compressive strength of ternary binder concrete with ggbs and limestone powder (Carrasco et al., 2005)

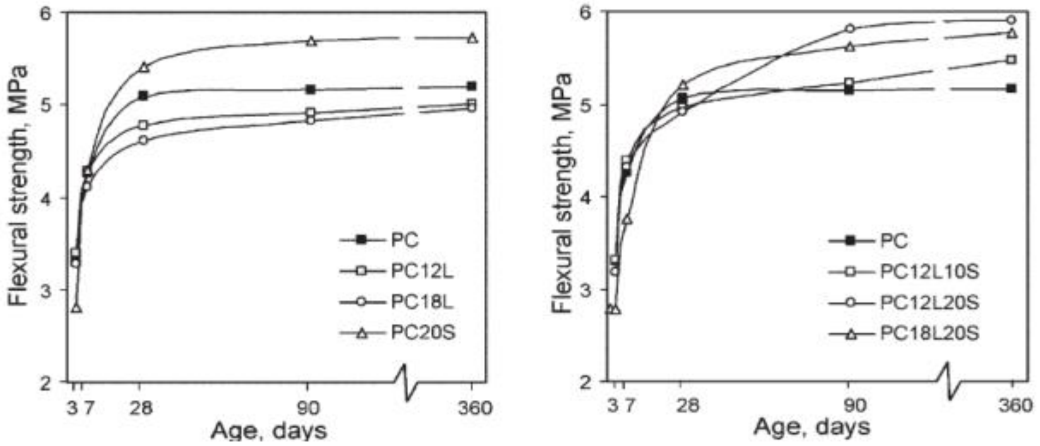


Figure 2-17 Flexural strength of ternary binder concrete with ggbs and limestone powder (Irassar et al., 2006)

2.5.1.4 Durability properties

A comprehensive study on the durability performance of ternary binder mixes with ggbs and limestone powder was carried out by Irassar et al. (2006), within which they conducted tests such as water absorption, sorptivity and chloride penetration. The water absorption of concrete specimens was measured by firstly removing all the moisture from the specimen by drying in an oven at 105±5°C for 24 hours and then fully immersing the specimens in water; the water absorption is recorded as the change in weight of the specimens after 48 hours of immersion. The results are shown in Figure 2-18. It can be seen that, referring to the graph on the left, mixes with limestone powder had lower water absorption at early ages compared to the reference Portland cement mix (PC) but achieved similar (PC12L) or slightly higher (PC18L) values at 360 days, whereas the mix with 20% ggbs (PC20S) had lower water absorption after 7 days. The ternary binder mixes, shown on the graph on the right, performed better than the PC mix at ages over 28 days, with mixes PC12L20S and PC18L20S having a lower water absorption value at 90 days compared to the binary ggbs mix PC20S. The first could be attributed to the positive effects of ggbs compensating for the shortcomings of limestone powder mixes whereas the latter could be attributed to the nucleation effect of limestone powder increasing the rate of Portland cement hydration leading to the secondary reaction with ggbs to occur earlier resulting in the formation of a denser pore structure.

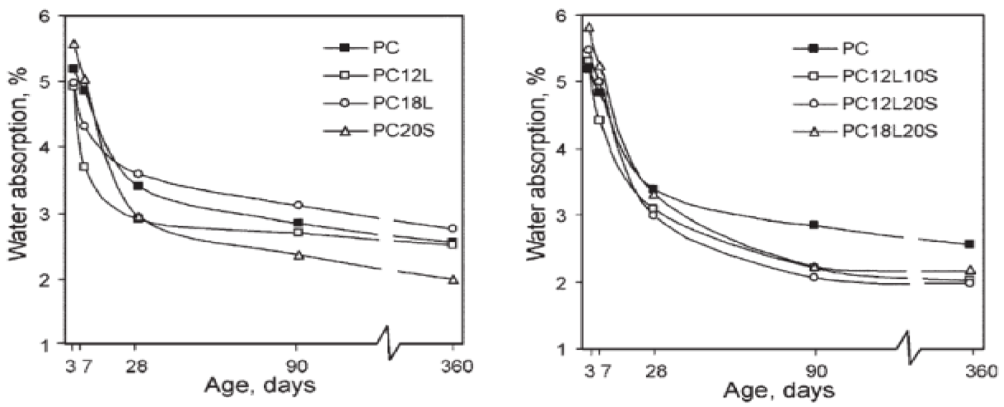
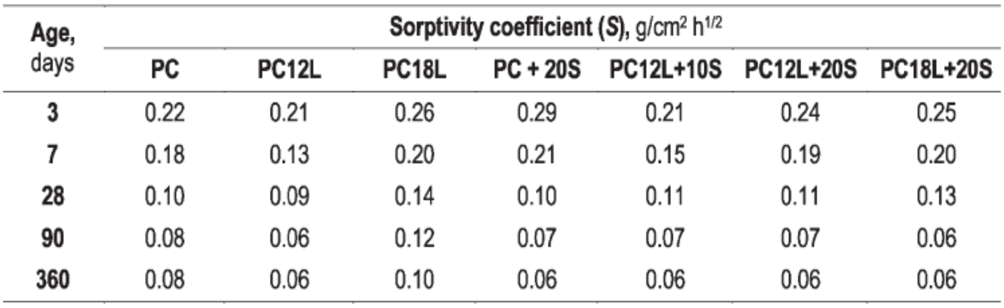


Figure 2-18 Water absorption of ternary binder concrete with ggbs and limestone powder (Irassar et al., 2006)

The sorptivity test was carried out on oven-dried cubes, with 4 side surfaces coated in epoxy (top face exposed to air and bottom face in contact with water) ensuring uniaxial absorption. The bottom face of the specimen was immersed in water (to a depth of 10mm) and weight measurements were taken at 1, 5, 15 and 30 minutes and 1, 2, 4, 6, 12, 24 and 48 hours after immersion; the sorptivity coefficient was obtained as the slope of the best-fit line of the graph of volume of water absorbed per unit area (in contact with water) against the square root of the time. The sorptivity coefficient values obtained are shown in Table 2-5. For all the concrete mixes tested, the sorptivity coefficient decreased with age. The sorptivity of the concrete mix with 12% limestone (PC12L) was lower at all ages than the reference Portland cement mix (PC), however increasing the limestone addition level to 18% (PC18L) resulted in a higher sorptivity coefficient, indicating increased vulnerability. As for the concrete mix containing 20% ggbs replacement (PC20S), the sorptivity coefficient of the mix was higher than the PC mix at early ages (up to 7 days) but after 28 days it appeared to have a lower sorptivity coefficient which could be attributed to the secondary reaction of ggbs resulting in a denser pore matrix at later ages. Comparing the coefficients of the ternary binder mixes (PC12L+20S and PC18L+20S), to that of PC20S, it can be seen that sorptivity coefficient was lower at early ages (up to 7 days), attributed to the filler effect of limestone powder, whereas at later ages (over 28 days), comparing to mixes PC12L and PC18L, the addition of ggbs caused a reduction in the sorptivity of the mixes due to its secondary reaction resulting in formation of denser matrix. This again demonstrates the complementary behaviour between ggbs and limestone powder in ternary binder mixes.

Table 2-5 Sorptivity coefficient of ternary binder concrete with ggbs and limestone (Irassar et al., 2006)



Age, days	Sorptivity coefficient (*S*), g/cm^2 h$^{1/2}$						
	PC	**PC12L**	**PC18L**	**PC + 20S**	**PC12L+10S**	**PC12L+20S**	**PC18L+20S**
3	0.22	0.21	0.26	0.29	0.21	0.24	0.25
7	0.18	0.13	0.20	0.21	0.15	0.19	0.20
28	0.10	0.09	0.14	0.10	0.11	0.11	0.13
90	0.08	0.06	0.12	0.07	0.07	0.07	0.06
360	0.08	0.06	0.10	0.06	0.06	0.06	0.06

The chloride ion profile results obtained by the study are shown in Figure 2-19. Two different curing regimes were used, either the specimens were air-cured (AC) (28-days in air) or moist-cured (MC) (6 days moist cured in lime saturated water and 22 days air cured). The specimens were then exposed to 3% NaCl solution (one face only, similar to the sorptivity test) for 180 or 360 days and powder samples were taken at various depths and the chloride ion content was determined. Referring to Figure 2-19, comparing the top left graph, reference Portland cement mix (PC), with the binary blend mix with 18% limestone powder (PC18L), top right graph, it can be seen that the chloride penetration is deeper in the binary binder mix. For example after 7 days moist curing (MC), at 180 and 360 days of exposure, the chloride ion concentration at a depth of 4cm, was about 1 and 3.5 kg Cl^-/m^3 respectively for PC18L mix compared to 0.2 and 1.5 kg Cl^-/m^3 respectively for PC mix. The mix with 30% ggbs (PC30S), bottom right graph, the chloride ion concentration is lower compared to the reference mix with a sharper drop in concentration with depth. In addition, the chloride concentration difference between 180 and 360 days of exposure is much smaller which could be due to the fact that the secondary reactions that occur with ggbs helps produce a denser pore matrix resulting in a reduction in chloride penetration. Finally looking at the ternary binder mix (PC12L+20S), bottom left graph, it can be seen that the chloride ion concentration is more than PC30S but less than PC18L and the reference mix. Here there is a complementary effect between these two powders in the sense that, when combined together, the positive effect of ggbs compensates for the negative effect of limestone powder on chloride ion movement through the pore matrix.

The pattern observed with the chloride ion profile is also mirrored by the rapid chloride penetration (RCP) test. Thomas et al. (2010) and Hooton et al. (2010) both concluded that the addition of solely limestone powder (over 10%) increased the total charge passed, showing that the concrete is more vulnerable to chloride penetration, whereas the addition of only ggbs improved the chloride penetration resistance of the concrete, as previously mentioned in sections 2.4.3.4 and 2.4.1.4 respectively. Tests on ternary binder mortar mixes made with Portland-limestone cement (15% limestone powder) and 30% ggbs (Hooton et al., 2010) and 35% ggbs (Thomas et al., 2010), both showed that the charge passed was lower than the reference Portland cement mix and lower than both respective binary binder mixes. Hooton et al. (2010) also performed sulphate resistance and alkali-silica reactivity tests on various mixes and concluded that, for both tests, the use of limestone by itself (15%) worsens the resistance of the mix however when combined with ggbs (30%), the risk of both sulphate and alkali-silica attack was minimised/eliminated.

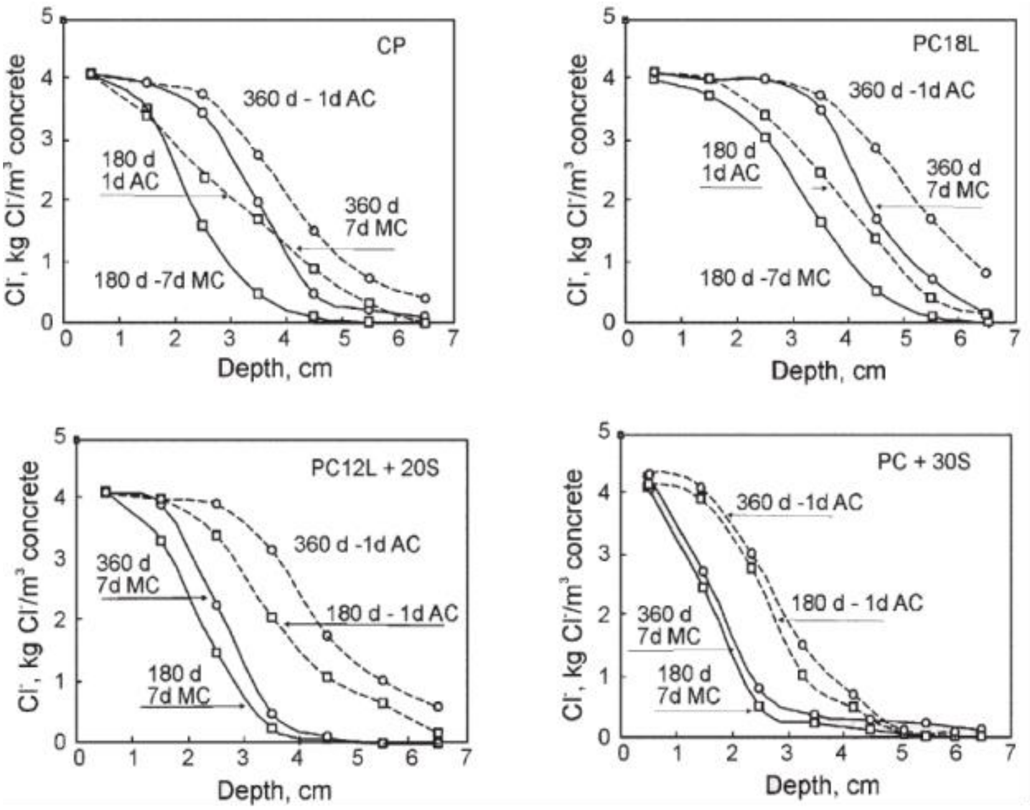


Figure 2-19 Chloride penetration profile for ternary binder concrete with ggbs and limestone (Irassar et al., 2006)

2.5.2 Ternary binders with limestone powder and fly ash

Several studies have been carried out on the effect of ternary blended binders containing limestone powder and fly ash on various properties of concrete, with the majority in the past 5 years. In this section the outcomes and conclusions of those studies are presented and discussed.

2.5.2.1 Fresh properties

Turkel & Altuntas (2009) observed that replacing 30% of the cement by limestone powder (PC30L) increases the spread value of the mortar from 218 to 260mm whereas the addition of 30% fly ash (PC30FA) resulted in a reduction in spread value to 205mm, which is not in agreement with the general literature stating that the addition of fly ash, due to its spherical particle shape, results in improved consistency. The results are illustrated in Figure 2-20. Considering the mix PC30FA, substituting 5% of the fly ash with limestone powder (PC25FA5L), resulted in an increase spread value to about 233mm which is also higher than the spread value of the control mortar mix (PC), however substituting 10% of the fly ash with limestone powder (PC20FA10L) did not affect the spread value. Georgescu & Saca (2009) also looked at the effect of fly ash and limestone powder on the consistence of mortar mixes. They reported that addition of fly ash or limestone powder separately or in combination resulted in a reduction in water demand (improved consistence). Wang et al. (2011) studied the effect of varying the limestone powder/fly ash ratio (total replacement level of 50%) and concluded that the greater the proportion of limestone powder resulted in improved consistence of the mix and better slump retention over 1 hour after mixing.

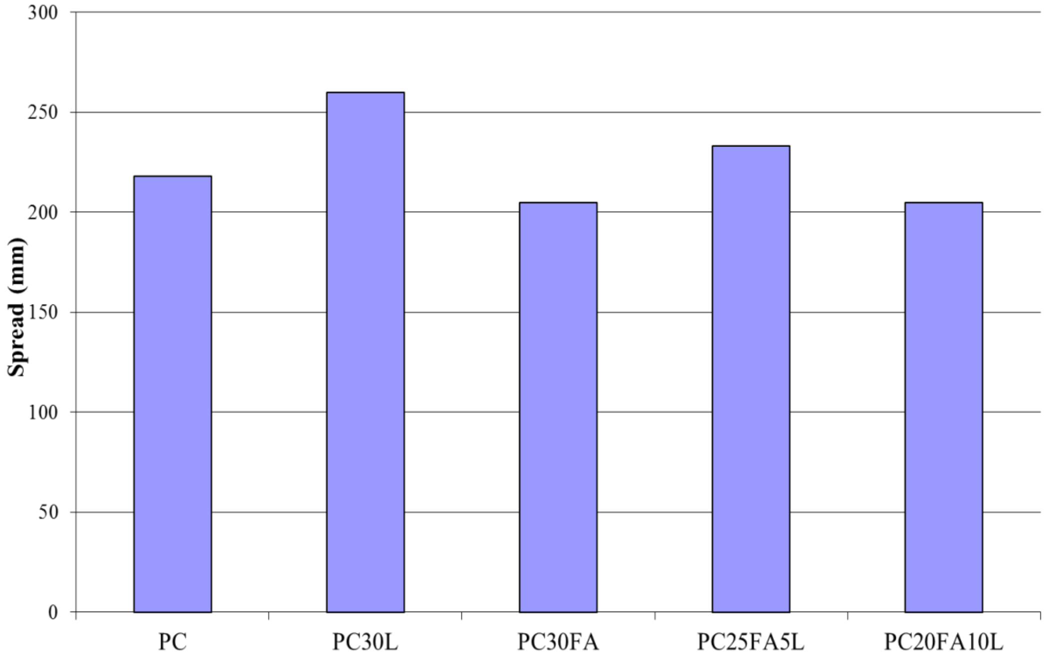


Figure 2-20 Spread value for ternary blend mortar mix with fly ash and limestone powder (Turkel & Altuntas, 2009)

2.5.2.2 Early age properties

The presence of limestone powder generally accelerated the setting time of the mix, however mixes which contained more fly ash than limestone powder seemed to have a longer setting time compared to the corresponding binary blend mix and vice versa (Mounanga et al., 2011). For example, with mixes having 50% cement replacement, the one containing 33% fly ash + 17% limestone had an initial and final setting time of 368 and 780min respectively whereas the mix containing 33% limestone + 17% fly ash has setting times of 325 and 600min respectively; the corresponding binary blend with 50% fly ash replacement had initial and final setting times of 381 and 681min respectively. The fineness of limestone powder also affects the mix setting time, with the finer limestone powder giving shorter setting times (Bentz et al., 2012).

Mounanga et al. (2011) studied the effect of having ternary binders consisting of fly ash and limestone powder on the different properties of the resultant mortar mix. As with the ggbs and limestone ternary binder mixes that they tested (2.5.1.1), part of the Portland cement was substituted with fly ash (binary binder) and then, to produce ternary blended binders, part of the fly ash was replaced with limestone powder as to keep the total replacement level unchanged. In their heat of hydration test results (Figure 2-21), partial replacement of fly ash with limestone powder resulted in an increase of the peak heat flow albeit still lower than the heat output of the Portland cement control mix. This could be attributed to the limestone powder increasing the cement hydration rate (the nucleation effect). This seemed to be the trend for all the mixes with the exception of one (50% total replacement level with fly ash and limestone replacement levels of 33 and 17% respectively) which had an unusually flattened heat flow curve (Figure 2-21b). Also, similar to ternary binder mixes with ggbs and limestone, when limestone replaces part of the fly ash, the time required to reach peak heat flow is reduced, this again could be due to the limestone increasing the rate of cement hydration resulting in an increase in the secondary pozzolanic reactions. They reported that for a concrete with 50% fly ash replacement, substituting 17 and 33% of that fly ash with limestone powder, the time to peak heat flow decreased from 616min to 550 and 416min respectively. A similar trend was seen for concrete with 25% fly ash replacement, when 8 and 17% of fly ash was substituted limestone powder, the peak heat flow time decreased from 586min to 503 and 442min respectively. The effect of increase in peak heat flow and reduction in time to reach this is greater with the increase in limestone fineness as the greater surface area will result in increased rate of both hydration and secondary pozzolanic reactions (Sato & Beaudoin, 2011; Bentz et al., 2012).

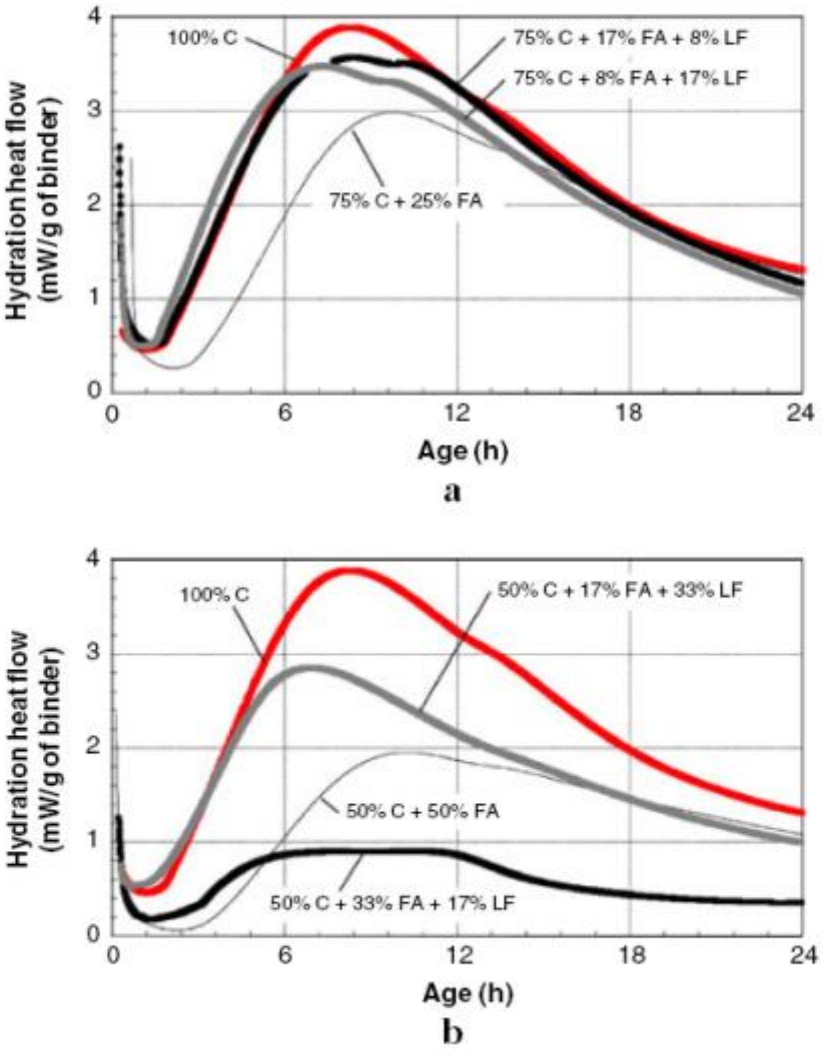
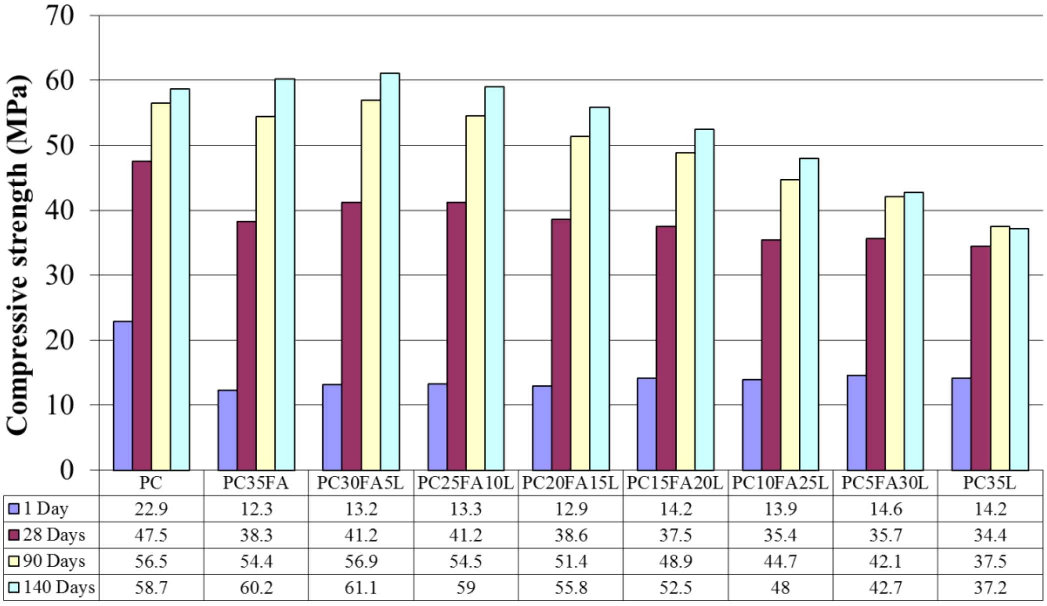


Figure 2-21 Hydration heat flow for ternary binder mixes with fly ash and limestone powder (Mounanga et al., 2011)

2.5.2.3 Strength

From the heat of hydration results in the previous section, it was concluded that the presence of limestone increased the cement hydration reaction leading to an increased rate of pozzolanic reaction at early ages. Increase in the rate of reactions would indicate an increase in the rate of formation of calcium-silicate hydrates hence an increase in early compressive strength. De Weerdt et al. (2011) studied the synergy between limestone powder and fly ash in ternary blend mixes. The compressive strength results are illustrated in Figure 2-22.



	PC	PC35FA	PC30FA5L	PC25FA10L	PC20FA15L	PC15FA20L	PC10FA25L	PC5FA30L	PC35L
■ 1 Day	22.9	12.3	13.2	13.3	12.9	14.2	13.9	14.6	14.2
■ 28 Days	47.5	38.3	41.2	41.2	38.6	37.5	35.4	35.7	34.4
□ 90 Days	56.5	54.4	56.9	54.5	51.4	48.9	44.7	42.1	37.5
□ 140 Days	58.7	60.2	61.1	59	55.8	52.5	48	42.7	37.2

Figure 2-22 Compressive strength of ternary binder mortar with fly ash and limestone powder (De Weerdt et al., 2011)

They kept a constant total cement replacement level of 35% and varied the fly ash/limestone powder percentages observing the changes in hardened mechanical properties of the mortar. Considering a mix with 35% fly ash replacement with no limestone powder (PC35FA), they noticed that substituting 5% of the fly ash by limestone powder (PC30FA5L), leads to slightly higher compressive strength at all ages albeit lower than the reference Portland cement mix (PC) at 1 and 28 days with similar strengths at 90 and 140 days (Figure 2-22). The mix with 15% replacement by limestone powder (PC20FA15L) however resulted in the same 28-day strength to PC35FA but a slight reduction in the 90 and 140-day strength. Comparing PC35FA mix with the ternary binder mixes, the 1-day compressive strength of the ternary binder mixes increased with increasing limestone powder replacement which is indicative of the heterogeneous nucleation effect of limestone powder resulting in increased rate of hydration reaction at early ages. Similar conclusions were also drawn by Yilmaz & Olgun (2008).

Looking at the change in the hydration products formed when limestone powder and fly ash are combined could shed some light on the synergistic effect observed between these two powders. XRD-spectra analysis showed that the substitution of 5% fly ash with limestone powder led to the formation mono-carboaluminate and hemi-carboaluminate hydrates instead of mono-sulphoaluminate hydrates hence the decomposition of ettringite to monosulphate is prevented (De Weerdt et al., 2011; De Weerdt et al., 2011b). Since ettringite is an expansive compound, this leads to an increase in the volume of the hydrates hence a decrease in porosity and thereby an increase in strength. Furthermore as fly ash reacts it provides additional aluminates within the pore matrix lowering the sulphate/aluminate ratio amplifying the impact of limestone (De Weerdt et al., 2011b).

De Weerdt et al. (2011) also tested the flexural strength of ternary binder mixes. The results are illustrated in Figure 2-23. The observed pattern in the flexural strength is similar to that of the compressive strength. For replacement level of up to 20% of the fly ash with limestone powder, the concrete seemed to have higher flexural strength at all ages with the maximum increase occurring at replacement level of 5%. Similar to the compressive strength results, the 1-day flexural strength of the ternary binder mixes increases, albeit slightly, with increasing limestone powder replacement due to the heterogeneous nucleation effect of limestone powder at early ages. Turkel and Altuntas (2009) noticed that, for a mix with total cement replacement of 30%, substituting 5% of fly ash with limestone powder (PC25FA5L) resulted in an increase in the flexural strength compared to the binary binder mix with only 30% fly ash replacement (PC30FA), however when the replacement level was increased to 10% (PC20FA10L), a slight reduction in the flexural strength was noticed at ages up to 28 days. Both studies conclude that there is some synergistic effect between fly ash and limestone powder when used in combination; however the extent of this effect seems to vary which would indicate that other factors of the powders (including Portland cement) such as chemical composition and fineness might well influence its extent.

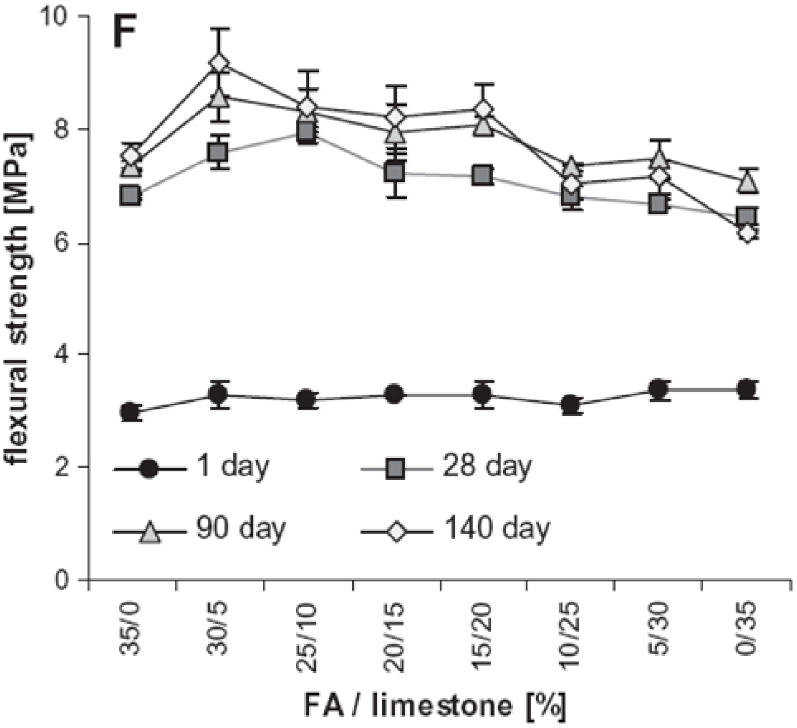


Figure 2-23 Flexural strength ternary binder mortar with fly ash and limestone powder (De Weerdt et al., 2011)

2.5.2.4 Durability properties

Most studies looking at the interaction between limestone powder and fly ash in concrete have only considered the fresh and hardened mechanical properties of concrete i.e. consistence and strength, hence there is a lack of literature available on the durability of ternary binder mixes with fly ash and limestone powder.

Turkel and Altuntas (2009) conducted water absorption tests on ternary binder mortar mixes and observed that the water absorption was higher than the reference Portland cement mix. Comparing the water absorption of mix PC25FA5L and PC20FA10L, there was a decrease in the water absorption (from 4.76% to 3.55%) which could be attributed to the filler effect of limestone powder. Vikan et al.

(2010) did not find any significant difference between the drying shrinkage of self-compacting concrete mixes made with binary or ternary blended binders with fly ash and limestone powder.

Georgescu and Saca (2009) looked at the variation in mechanical strengths of mortar mixes when immersed in two different acid solutions (hydrochloric acid and acetic acid) for 60, 90 and 360 days. The study concluded that ternary blend mixes with fly ash and limestone were more stable in the acid solutions than binary blend mixes with fly ash alone, which was attributed to the denser pore structure (lower porosity) of the mix due to the presence of limestone powder. Liu et al. (2010) tested the expansion of mortar prisms kept in a magnesium sulphate solution for 90 days (after 28 days of water curing). Their results indicate that the mortar mixes incorporating limestone powder and fly ash separately and in combination had lower expansion values compared to the reference Portland cement mix hence higher magnesium sulphate resistance. After 90-day immersion, the reference Portland cement mix had the highest expansion followed by binary binder mix with 50% fly ash replacement then by ternary binder mix (30% limestone powder and 20% fly ash) and lastly the mortar mix with 50% limestone powder replacement which gave the lowest expansion value of all mixes tested. The ternary binder mix gave a lower expansion value than the binary binder mix with 50% fly ash indicating better magnesium sulphate resistance.

2.6 Discussions with industry

During the initial period of this research project, meetings were held with various industrial personnel from the concrete construction industry to discuss their views on the research required on methods or ways of producing more sustainable concrete. These ranged from raw material suppliers to concrete users, with the aim of better understanding the research needs of the industry. Discussions were held with aggregate suppliers, binder suppliers i.e. Portland cement, ggbs and fly ash and concrete users. A summary of the outcomes of these discussions is given in this section with detailed minutes of the meetings in Appendix 2.

The research direction suggested by two aggregate suppliers was to look at greater utilisation of recycled aggregates or lightweight aggregates, reducing the use of natural aggregates (both fine and coarse) hence lessening the environmental impacts of aggregate dredging and quarries. Bromwich (2009), technical manager of Lafarge Aggregates, believed that with further research there is a potential of using higher percentage replacements of recycled aggregates in concrete, including recycled concrete aggregates. Discussion with Newport (2009), Director of Sustainability Research Institute from University of East London, was mainly about the idea of using novel lightweight aggregates in concrete produced by blending waste powders (45% clay, 45% fly ash and 10% sewage sludge ash) which he was producing in his laboratories.

As majority of the work on reducing the carbon footprint of concrete was focused around replacing part of the Portland cement with ggbs and fly ash, meetings were held with the suppliers of these binders, one supplier per binder. The key point from discussions with the technical development manager of Hanson Cement was that the cement industry has been continuously trying to reduce their carbon emissions by improving the efficiency of the production line. However this has almost reached its limit and now, with increasing pressure on them to further reduce their carbon emissions, he believed the way forward would be for increase in production of blended binders instead of pure CEM I Portland cement (Ashby, 2009). Hence the suggestion was for further research on the use of cement replacement materials, with one being the use of asphalt plant dust (APD) which is a by-product produced from the asphalt plant. Ashby was also able to discuss ggbs because when initial contact was made he was part of the Civil & Marine Ltd. His suggestion was to investigate the effect of the source and fineness of both the clinker and ggbs on the performance of Portland cement/ggbs blended binders (Ashby, 2009). For fly ash, a meeting was held with the technical director of UK Quality Ash Association who suggested investigating further the use of incinerator bottom ash, as fly ash has already been widely used in the concrete industry, and understand not only the physical but also the chemical reasons behind its effect on concrete properties when used as a Portland cement replacement (Sear, 2009).

Discussions were also held with two users of concrete. The first meeting was with the materials consultant of Arup. One comment was that using new waste materials in concrete (as a cement replacement materials or otherwise) for which the effects on the performance of the concrete is not very well understood (both short and long-term performance), and so companies such as Arup are then reluctant to specify the use of these concretes for their projects (Marsh, 2009). Marsh (2009) also seemed to agree with the point made by Ashby (2009) about the need for the cement industry to move towards producing more blended binders as the improvement in cement production efficiency has almost reached its limit. He also emphasised that to justify the use of any waste or by-product material in concrete issues of location of waste, quantity of waste available, price, chemistry variability from one batch to next, additional processing requirements, percentage replacements possible and lastly the effects on the fresh, hardened mechanical and durability properties of the concrete would all need to be considered. Hence Marsh (2009) suggested that a good research path would be to investigate the use of ternary blended binders incorporating limestone powder, ggbs and fly ash as this has not been done extensively; also concrete users are familiar with the performance of and comfortable with these materials hence they would be much less reluctant to specify such concrete for projects. His reasoning for the necessity of this research was that as the cement industry would, in the near future, increase the production of blended cements, the easiest addition to incorporate for the cement industries would be limestone powder, as this is already used as a raw material for the production of cement. Hence the issue was that if the cement industry was to, in the near future, begin producing more Portland-limestone cement then the use of blends of this with ggbs or fly ash (i.e. producing ternary blends) becomes attractive providing the resulting properties are known and documented. The second meeting was held with the technical director of British Ready-Mixed Concrete Association (BRMCA), where the outcomes of the discussions confirmed those of the discussions with Marsh (2009). He agreed with the idea that the cement industry has reached its production efficiency limit and does need to find other methods of further reducing its carbon footprint and that the increase in production of blended cement with limestone powder seems like the most likely and cost-effective short to medium-term solution that they would opt for (Harrison, 2009). Hence he also suggested that if that was the path the cement industry would opt for then the concrete producers and companies who currently specify concrete mixes made with binary blends need to know, in the near future, the changes in the performance of the concrete when the primary binder will be Portland-limestone cement.

Discussions with industrial personnel are very valuable for researchers as it provides them with an insight to the problems currently faced and the gap in knowledge within the industry. With this, the author believes one would be able to better formulate a project which would be of a scientific value from an academic point of view and at the same time help address one or more of the current issues faced by the industry. In relation to this work, these discussions were of great value to forming the aims and objectives of the project (Chapter 3), as it firstly showed that the concrete construction industry is aware of its environmental impacts i.e. release of harmful emissions and high carbon footprint, and is continuously striving to reduce these and become one of the leaders in sustainable construction within the industry. Secondly, their views and suggestions on the research required provided the author with better understanding of the current gap in knowledge within the industry.

2.7 *Conclusions*

In this section, conclusions drawn from the literature review are given.

1. Concrete mixes having a slump value of greater than 200mm can be classified as high-consistence concrete. The development of high-consistence concrete, made possible due to advances in admixture technology, has been increasingly used in recent years. It offers various advantages such as the ability to be placed with minimal vibration in areas of congested reinforcement and with reduced labour and shorter time. Disadvantages include higher cost due to the high Portland cement content and use of admixtures to achieve the required fluidity and stability of the mix. There are different types of high-consistence concrete such as flowing concrete, underwater concrete and self-compacting concrete, each of which has additional requirements.

2. Various test methods have been developed to assess the fresh properties of these concrete types. For flowing concrete, the conventional slump test and flow table test can be used to assess its consistence. Underwater concrete, in addition to high consistence, must be resistant to washout for which can be assessed with the plunge, stream or drop tests. Self-compacting concrete has three features which makes it different from other concrete types. It must flow under its own weight (filling ability), it should pass through restricted area without blocking (passing ability) and it must stay homogeneous and not segregate during transport, placement and after placement (segregation resistance). Five test methods have been developed and standardised for assessing each of these features: the slump flow test and the V-funnel test for filling ability, the L-box test and the J-ring test for passing ability and the sieve segregation test for assessing the segregation resistance.

3. Fly ash and ggbs have been used in concrete, as cement replacement materials, for over 30 years. With the high production rate of fly ash and ggbs, along with the immense pressure on both the cement and concrete

industry to reduce their carbon footprint, there is an incentive to incorporate these in concrete as they reduce the cement content and hence the concrete’s carbon footprint and cost. Furthermore the physical and chemical effects of both fly ash and ggbs can improve the performance of concrete. Advantages include improved consistence (less use of admixtures), increase in long-term strength and improved durability properties; the main disadvantages are reduction in the early-age strength and slower strength gain at early ages.

Typical replacement levels for ggbs and fly ash are about 50 and 30% respectively. Due to its hydraulic nature, ggbs replacement levels can be as high as 95% whereas for fly ash, which is a true pozzolan, maximum replacement levels are about 55%. Production of high-volume fly ash (HVFA) concrete, where over 50% of cement if replaced by fly ash, is possible by using a low water/cement ratio, ensuring satisfactory early strength and strength development, and chemical admixtures to ensure satisfactory fresh properties. Various studies have demonstrated the possibility of producing concrete mixes with fly ash replacement ranging from 50 to 80% with adequate mechanical properties.

Over the past 20 years or so, researchers have been investigating methods of improving the reactivity of ggbs and fly ash in concrete. One or more of three treatment methods are usually utilised; mechanical treatment (increasing fineness of addition), thermal treatment (curing at higher temperatures) and chemical treatment (addition of chemicals), with the latter being the most effective method. In this, the reactivity of ggbs and fly ash is improved by increasing the alkalinity of the pore solution. These are known as alkali-activated cements. Improvements in early-age strength, strength development and also higher long-term strength relative to Portland cement mixes have been achieved. However, the reaction mechanisms are very complex and are not fully understood. Also there are some concerns regarding the durability performance and the effects of chemical admixtures on their performance are not fully understood, as the majority of admixtures are for Portland-cement based concrete and do not seem to work well with alkali-activated cement concrete.

4. Limestone powder (ground calcium carbonate) has been used in concrete as a cement replacement material for many years well before the initial utilisation of ggbs and fly ash. It has been and is still being incorporated in Portland cement as the allowable minor addition (up to 5%). In the past, the maximum allowable replacement level of limestone powder was set at 20% however the current standard, BS EN 197-1 (2011), has increased this to 35%. Limestone powder has been widely classified as a Type I (nearly inert) addition in concrete, not taking part in any chemical reactions, however studies have shown that this is not totally the case and that it does react with the tri-calcium aluminate in the cement accelerating the primary hydration reaction. The physical effects of limestone powder are the filler effect, as it is finer than Portland cement it changes the initial porosity of the mix (improved freeze-thaw resistance), heterogeneous nucleation effect, the greater available surface area for nucleation accelerating the hydration reaction (hence increasing early-age strength development and strength at early ages) and the dilution effect as the addition of limestone powder reduces the amount of Portland cement available to hydrate (lower long-term strength). Apart from freeze-thaw resistance, other durability properties of the concrete seem to worsen with the increase in addition levels of limestone powder (>10%). Studies have shown that increasing the fineness of limestone powder increases the impact of the heterogeneous nucleation effect and the filler effect. Portland-limestone cements are produced at various cement plants across the UK; however these have not been used to any great extent.

5. Over the past two decades, numerous studies have looked at mixes with ternary and quaternary blended binders with the main intentions of seeing whether it is possible to combine the benefits of each addition and, in some cases, to see whether one addition can compensate for the shortcoming of the other. The majority of the studies looked at the effects of having ternary and quaternary blended binder incorporating Portland cement, ggbs, fly and silica fume on various concrete properties. Many showed that the addition of 10% silica fume in combination with ggbs or fly ash improved the early-

age strength, compensating for the shortcomings of ggbs and fly ash, and in turn ggbs and fly ash increased the consistence of the mix, compensating for one of the disadvantages of using silica fume. Over the past 5 years, a number of studies have investigated the effects of having ternary blended binders with Portland cement and limestone powder in combination with ggbs or fly ash. This is indicative of increased interest in this topic and realisation of potential advantages limestone powder could offer.

Studies looking at ternary blended binders with ggbs and limestone powder all reported that there are some complementary effects between these two powders. The presence of limestone powder increased the rate of primary hydration reaction, resulting in an increase in early-age strength complementing ggbs and consequently leading to an increase in rate of the secondary hydration reaction with ggbs as the rate of formation of calcium hydroxide is increased. The complementary effects due to the presence of ggbs were improved slump retention, improved long-term strength and improved durability properties of the mix for instance lower water absorption, lower sorptivity coefficient and lower chloride penetration.

As with the limestone powder/ggbs combinations, the few studies investigating the effects of limestone powder/fly ash combinations also reported some synergistic effect between these two powders. Similar complementary effects were observed due to limestone powder resulting in increased strength at early ages. As with ggbs, the fly ash improved the slump retention and the long-term strength. There is very little literature on the effects of this binder combination on the various durability properties; however from those available, one suggested that the incorporation of limestone improves the water absorption of the mix and the other that ternary blend mixes were more stable in acid solution compared to their relative binary blend mixes.

6. Meetings held with industrial personnel confirmed the industry’s awareness of the current sustainability issues faced i.e. reducing harmful emissions, and their continuous efforts to address them. Their views on the research

required to produce more sustainable concrete revealed the current gap in knowledge within the industry.

Chapter 3 Aims and Scope of Research

3.1 Conclusions from literature review

The conclusions from the literature review (Chapter 2) which are relevant to this research project are listed below.

- High-consistence concrete (HCC), such as self-compacting concrete, has attained worldwide interest due to the various advantages it offers and its use has increased over the past decade and, with designs becoming more complex, will continue to increase in the future.

- HCC requires high quantities of Portland cement or similar powder along with chemical admixtures such as superplasticisers to attain adequate fluidity and stability. As the powder portion does not necessarily need to be Portland cement, there is the potential for using greater quantities of cement replacement materials for both technical (e.g. lower heat of hydration, improved durability) and environmental (e.g. reduce waste to landfill, reduced cement content) advantages.

- Fly ash and ggbs have been extensively utilised in concrete replacing part of the Portland cement and their advantages, disadvantages and limitations have been well researched and documented. Advantages include improvement in long-term strength and durability properties with decrease in strength at early ages being the disadvantage. Their replacement levels of are limited by the concrete performance.

- Limestone powder has also been extensively used in concrete. It could lead to more uniform pore size distribution (due to the filler effect) and increased rate of hydration reaction at early ages (due to the nucleation effect) resulting in higher strength. However the downsides are decrease in the long-term strength (due to the dilution effect) and the durability properties seem to worsen with limestone powder replacement levels above 10%. Hence, as with ggbs and fly ash, the replacement levels of limestone powder is limited by the performance of the concrete.

- Previous investigations on ternary and quaternary blended binders with Portland cement, fly ash, ggbs and silica fume revealed promising results showing some complementary effects between the different additions where, in some cases, each powder would compensate for the shortcomings of the other and vice versa.

- Some recent studies have looked at the use of ternary binders incorporating Portland cement, limestone powder and ggbs or fly ash. The use of these binders, in combination, complemented each other where the presence of limestone resulted in an increase in the early-age strength whereas ggbs and fly ash fulfilled their role of increasing the long-term strength. More importantly, the presence of ggbs improved the durability performance of the mix compensating for the negative effects of limestone powder.

  However the number of studies on this topic is limited, especially on limestone/fly ash combination, and majority of them have been carried out investigations on the mortar components of normal-consistence concrete and not on high-consistence concrete where the scope could be much greater. In addition most studies focused on the effects of these binders on the fresh and hardened mechanical properties and not on the durability properties which is of great importance in concrete design.

- Discussions with industrial personnel have indicated that more systematic information on the performance of these blends could lead to their widespread use.

3.2 Overall objective

The use of high-consistence concrete has been and will continue to increase in the construction industry. The objective of the current project was to extend the scope of previous work and investigate the use of ternary blended binders of Portland cement and limestone powder (as primary binder) along with ggbs or fly ash, in three types of high-consistence concrete i.e. flowing concrete (FC), underwater concrete (UWC) and self-compacting concrete (SCC), broadening the quantity and combinations of additions available for use in high-consistence concrete. The fresh, hardened mechanical and durability properties of the concrete were evaluated.

Over the past few years, both the cement and concrete industry have come under scrutiny due to their environmental impacts (especially greenhouse gas emissions) which has lead both industries actively trying to significantly reduce these impacts. Hence this reinforces the need for this research as it can firstly allow the cement manufacturers to increase their production of Portland-limestone cement i.e. producing less pure Portland cement hence reducing their net Portland cement production and consequently their harmful emissions. Secondly it would demonstrate to the concrete producers and users the changes in the performance of the concrete when blending Portland-limestone cement with ggbs or fly ash which if used, will result in reduced carbon footprint and cost of the concrete. Concrete users are familiar with the performance of and comfortable with these materials when used individually and hence would be much less reluctant to specify such concrete than say alternative cements.

3.3 Aims of research

Having set out the overall objective, the main aims of this research are:

1. Feasibility of producing high-consistence concrete using ternary blended binders with Portland cement, limestone powder and ggbs or fly ash combinations without compromising its main properties?

2. Could the use of limestone powder in combination with either ggbs or fly ash, as ternary blended binders, result in each powder compensating for the shortcomings of the other leading to a better concrete?

   In other words, would the use of limestone powder lead to higher early-age strength compensating for the shortcomings of ggbs and fly ash and would the presence of ggbs or fly ash compensate for limestone powders' shortcomings i.e. long-term strength and durability?

3. How significant is the reduction in total embodied carbon and total embodied carbon/unit strength due to the reduction in Portland cement content in ternary blended binders?

3.4 Choice of tests

The various fresh and hardened property tests available were described in sections 2.2 and 2.3. This section explains the choice of these tests. The test procedures are explained in Chapter 4.

3.4.1 Fresh property tests

Among the available tests mentioned in 2.2, the following were chosen for each type of concrete:

- SCC: slump flow, V-funnel, J-ring and sieve segregation tests
- FC: slump and flow table test
- UWC: slump, flow table and washout tests

3.4.2 Hardened property tests

Here the choices of the hardened property tests are explained.

- *Hardened mechanical tests*: As mentioned in section 2.3, to assess the hardened mechanical properties two typical tests were chosen i.e. the compressive and cylinder splitting tests.

- *Non-destructive tests*: Among the available tests described in section 2.3.1, the dynamic elastic modulus and ultrasonic pulse velocity tests were chosen for this research. As mentioned the main advantages of these tests is that they can be used to assess various properties of concrete and can be performed repeatedly on any specimen without damaging the concrete. The dynamic elastic modulus test, as the name suggests, can be used to give an indication of the concrete stiffness which can be useful for structural design and the latter can be used to assess any defects in the concrete but also, as their results have a relationship with concrete strength, this can be an efficient and cost-effective method for continuously assessing the concrete strength without destroying the specimen.

- *Durability tests*:
    - Water absorption tests: The capillary rise method is relatively simple, quick and convenient and hence was chosen for this research. Various factors affect the sorptivity such as size of specimen, curing conditions, drying temperature, relative humidity and ambient temperature; hence they should be kept constant and also the drying temperature should be sufficiently low to prevent micro cracking (2.3.2.1).
    - Chloride resistance tests: The Rapid Chloride Penetration test was chosen to assess this property. Although this test has a number of shortcomings and limitations (2.3.2.2), it is still a useful standardised test which is relatively quick and the results are easy to interpret and compare being only a value

of charge passed. Nevertheless it is important to understand the limitations of this test and use the results with caution. It also has a simple and convenient set-up and test procedure.

3.5 Test programme

The stages and scope of the test programme, summarised in Table 3-1, were:

Stage 1: Selection of mix proportions, mixing procedures and test methods, target properties and constituent materials

Stage 1-1 Selection of mix proportions

The mix used for FC was based on that developed by Building Research Establishment (BRE) (1997).

No standard mix design was available for UWC hence typical recommended values for coarse aggregate content and sand/total aggregate ratio were obtained from the literature and used to design the mix.

The SCC was designed using a method developed at UCL which is simple and efficient; it is based on the use of correlations between the properties of mortar and concrete and was developed using readily available local materials. The use of mortar in the early stages is an advantage as the sample size is smaller, making it easier to handle and test.

Stage 1-2 Mixing procedure and test methods

The mixing procedure for mortar and concrete was fixed and used throughout this project; it ensured maximum powder dispersion and superplasticiser efficiency.

Standard consistence tests were used for assessing the fresh properties of FC and UWC, with a non-standard test for assessing the washout of UWC. For assessing the three characteristics of SCC a combination of recently standardised tests was used.

Stage 1-3 Selection of target properties for the control mixes

For FC a slump value of 200 – 240mm was chosen.

The chosen target properties for UWC were a slump value in the same range as for FC and a washout resistance of ≤ 15%.

For SCC, the target properties were selected based on the European guidelines (EFNARC, 2005) as adequate for normal applications. The chosen target values were an average slump flow value of 700mm (Class SF2), V-funnel time of around 8s (Class VF2), J-ring step height of less than 15mm using a narrow-gap J-ring with 41mm bar spacing (Class PA2) and segregation index of less than 15% (Class SR2).

Stage 1-4 Selection of constituent materials

The choice of aggregates (fine and coarse), Portland cement (PC), fly ash (FA), ggbs and limestone powder (LP) was based on convenience and local availability. To eliminate the effects of batch to batch variations in chemical properties of the powders and the amount of fine particles (<0.125mm), a single batch of each powder type and fine aggregate was used throughout the testing programme. Three different types of limestone powder were used each having different fineness. Tests were carried out to find the optimum combination of limestone powder having the lowest water requirement indicating high packing density (indirectly) which was then used throughout the testing programme.

In this project, three different chemical admixtures were used, a polycarboxylate-based superplasticiser (SP), Sika ViscoCrete 10, a viscosity-modifying agent (VMA) (for SCC), Sika Stabiliser 4 and an anti-washout admixture (AWA) (for UWC), Sika UCS Powder. The VMA was only used if the target fresh properties of SCC could not be obtained by using superplasticiser alone. All the admixtures were commercially available in the UK and ordered from one supplier, Sika (UK) Ltd, to ensure compatibility.

Stage 1-5 development of reference control mix for SCC, FC and UWC

A reference control mix meeting the target requirements given above was designed for each of three types of concrete with Portland cement as the sole binder.

Stage 2: Production and testing of SCC incorporating binary and ternary blended binders

Further concrete mixes, having the target fresh properties, with binary and ternary blended binders were produced and specimens cast for testing the hardened properties. The mixes were produced by replacing part of the Portland cement in the reference control mix. The replacement levels (by volume) of the additions for the binary blended binders were:

- Limestone powder at replacement levels of 10, 20 and 30%
- GGBS at replacement levels of 20, 40, 60 and 80%
- Fly ash at replacement levels of 20, 40, 60, and 80%

Having the correlation between the mortar and concrete properties, initially the spread and V-funnel tests on mortar mixes was used to get the required dosage of chemical admixtures (SP and, if necessary VMA) for all the addition levels. The corresponding concrete mixes were then produced and, if needed, the admixture dosages were adjusted for each mix to achieve the target properties.

Concrete mixes with ternary blended binders were then produced. A binary blended binder of Portland cement/limestone stone powder with ratio of 80/20 (by volume) was chosen as the base binder and part of that was then replaced with ggbs or fly ash producing ternary blended binders keeping the PC/LP ratio constant. The replacement levels were same as the binary mixes, 20 – 80% with increments of 20%. Again, the admixture dosages were adjusted if necessary.

The hardened properties of the concrete mixes were then measured at ages of up to 91 days. Tests included compressive strength, tensile splitting strength, dynamic elastic modulus (Ed) and ultrasonic pulse velocity (UPV), and for durability, sorptivity (water absorption) and the rapid chloride penetration (RCP).

Stage 3: Production and testing of FC incorporating binary and ternary blended binders

The aim here was also to produce a set of concrete mixes, FC instead of SCC, with binary and ternary blended binders, having the target properties, and assess their hardened properties. Having produced and tested SCC with wide range of replacement levels, it was decided to use the replacement levels which gave the best performance in SCC mixes to reduce the number of mixes in this stage. The limestone powder replacement level was kept constant at 20% (to keep the base binder constant) and replacement levels of ggbs and fly ash were 40 and 20% respectively.

The same set of tests as in Stage 2 was used to assess the hardened properties of the concrete mixes.

Stage 4: Production and testing of UWC incorporating binary and ternary blended binders

The same steps were followed here as in Stage 3, with the same replacement levels, the only difference being the concrete type was UWC instead of FC.

The same set of tests, as in Stage 2, was used to assess the hardened properties of the concrete mixes.

Table 3-1 Scope of test programme

Stage	Objective	Outcome	Refer to
1-1	Selection of mix design	FC: Simple mix design based on BRE (1997) UWC: Typical values chosen from literature SCC: Mix design developed by UCL	Chapter 6
1-2	Selection of mixing procedure and test methods	Fixed mixing procedure developed by Jin (2002) for optimum powder dispersion and SP efficiency FC: slump test and flow table test UWC: slump test, flow table test and washout test SCC: slump flow, V-funnel, J-ring and sieve segregation tests	Chapter 4
1-3	Selection of target properties	FC: slump 220 ± 20mm UWC: slump 220 ± 20mm, washout ≤15% SCC: slump flow 700 ± 50mm V-funnel time 8 ± 3s J-ring step height ≤15mm Segregation index ≤15%	Section 2.2.3 and Table 2-1
1-4	Selection of constituent materials	➢ Natural aggregates of size class 0/4, 4/10 and 10/20mm ➢ Ferrocrete Portland cement CEM I class 52.5N supplied by Lafarge Cement UK Ltd ➢ GGBS supplied by Hanson Cement (UK) ➢ Fly ash supplied by RockTron ➢ Limestone powder supplied by Omya (UK) ➢ Admixtures: Sika ViscoCrete 10, Sika Stabiliser 4 and Sika UCS Powder, all supplied by Sika (UK) ➢ Ordinary Tap water as mixing water	Chapter 5
1-5	Development of reference control mix	A reference control mix for each type of concrete was produced using the mix design, constituent materials and having the target properties mentioned.	Chapter 6
2	Production and testing of SCC incorporating binary and ternary blended binders	**Powders:** PC, LP, GGBS, FA	Chapter 7
		Types of blends: PC/LP, PC/GGBS, PC/FA, PC/LP/GGBS, PC/LP/FA *Note: LP is a 75%/25% combination of B10/B45 limestone powders*	
		<u>**Blend compositions**</u> **Binary blends:** PC/LP replacements of 10, 20 and 30%. PC/GGBS and PC/FA replacements of 20, 40, 60 and 80% **Ternary blends:** PC/LP (4:1 ratio) is used as base binder and that is then replaced with GGBS and FA at 20, 40, 60 and 80% producing PC/LP/GGBS and PC/LP/FA respectively.	
		<u>**Testing**</u> **Fresh properties:** Immediately after mixing **Hardened properties:** At age of 1, 3, 7, 28, 56 and 91 days	
3	Production and testing of FC incorporating binary and ternary blended	**Powders:** PC, LP, GGBS, FA	Chapter 8
		Types of blends: PC/LP, PC/GGBS, PC/FA, PC/LP/GGBS, PC/LP/FA *Note: LP is a 75%/25% combination of B10/B45 limestone powders*	

	binders	**<u>Blend compositions</u>** **Binary blends:** PC/LP replacements of 20%. PC/GGBS and PC/FA replacements of 40 and 20% respectively. **Ternary blends:** PC/LP (4:1 ratio) is used as base binder and that is then replaced with 40% GGBS and 20% FA producing PC/LP/GGBS and PC/LP/FA respectively.	
		<u>Testing</u> **Fresh properties:** Immediately after mixing **Hardened properties:** At age of 1, 3, 7, 28, 56 and 91 days	
4	Production and testing of UWC incorporating binary and ternary blended binders	**Powders:** PC, LP, GGBS, FA	Chapter 8
		Types of blends: PC/LP, PC/GGBS, PC/FA, PC/LP/GGBS, PC/LP/FA *Note: LP is a 75%/25% combination of B10/B45 limestone powders*	
		<u>Blend compositions</u> **Binary blends:** PC/LP replacements of 20%. PC/GGBS and PC/FA replacements of 40 and 20% respectively. **Ternary blends:** PC/LP (4:1 ratio) is used as base binder and that is then replaced with 40% GGBS and 20% FA producing PC/LP/GGBS and PC/LP/FA respectively.	
		<u>Testing</u> **Fresh properties:** Immediately after mixing **Hardened properties:** At age of 3, 7, 28, 56 and 91 days	

Chapter 4 Mixing Procedures and Test Methods

In this chapter the mixing procedures and test methods for the paste, fresh mortar and concrete and hardened concrete are briefly described. The relevant standard for each test is also given where applicable. Similarly the test methods for the constituent materials are also explained. All the tests were available at the beginning of the research apart from the Rapid Chloride Penetration (RCP) test, the plunge test for the underwater concrete and the heat of hydration (conduction calorimeter) test for the powders. Apparatus for RCP and the plunge test were assembled at UCL during the early stage of the experimental work, and the conduction calorimeter tests were carried out at Heriot-Watt University.

In order to obtain accurate and comparable results, the mixing procedures and test methods were kept as identical as possible throughout the research project i.e. consistent materials, mixing procedures and testing methods for all mixes, carried out with the same equipment, by same operator and in the same laboratory environment. All the constituent materials were stored at room temperature (20±2°C) with all the mixing and testing being carried out at this temperature.

4.1 Mixing procedures

For pastes, 0.7 litre batches were mixed in a Silverson mode RBXL high shear mixer. To provide efficient mixing, the mix water was first put in the bowl, the mixer then turned on and the powder then poured in gradually. The mixing time was about 10 minutes or until all the powder was well mixed with the water.

For mortar mixes, 2.7 litres batches were mixed in a Hobart bench mounted mixer with a maximum capacity of 10 litres. A Liner Cumflow mixer with a maximum capacity of 60 litres was used for concrete mixes. This is a forced action pan mixer which was robust and in good working condition. 60 litre batches of concrete were mixed for fresh property tests and subsequent casting of specimens for hardened property tests. The mixing procedure for both mortar and concrete mixes was based on the work done by Jin (2002) to achieve maximum superplasticiser efficiency and full dispersion of the powder. The procedure was as follows:

1. The mix water was divided into two parts of 80% and 20%. The superplasticiser was mixed with the 20% fraction.
2. The required quantities of the powder and aggregate were weighed out, placed in the mixer and mixed for 1 minute.
3. The 80% fraction of water was then added slowly during a further minute of mixing.
4. The final 20% fraction of water including the admixture was then added over a further one minute.
5. Mixing was carried on for a further 4 minutes. The mix was then allowed to stand for 3.5 minutes and then mixed for a final 30 seconds.

4.2 Tests on constituent materials

This section briefly describes the tests carried out on the constituent materials i.e. powders and fine and coarse aggregates.

4.2.1 Test on powders

The reaction between Portland cement and water is an exothermic chemical reaction therefore heat is liberated during the reaction which is known as the heat of hydration. Monitoring and measuring the heat evolution of hydrating cement can give information on the rate of and total heat output which can be used to evaluate the hydraulicity of the cement. Hence this test was carried out to compare the early hydration behaviour of the different binder blends.

There are two standardised methods for measuring heat of hydration of cement; the solution method and the semi-adiabatic method given in BS 196-8 (2010) and BS

196-9 (2010). There also is a third more common but non-standardised method using a conduction calorimeter; the tests for this research were carried out on our behalf by Heriot-Watt University using a JAF Isothermal Conduction Calorimeter (Figure 4-1 and Figure 4-2).

Figure 4-1 JAF isothermal conduction calorimeter set-up

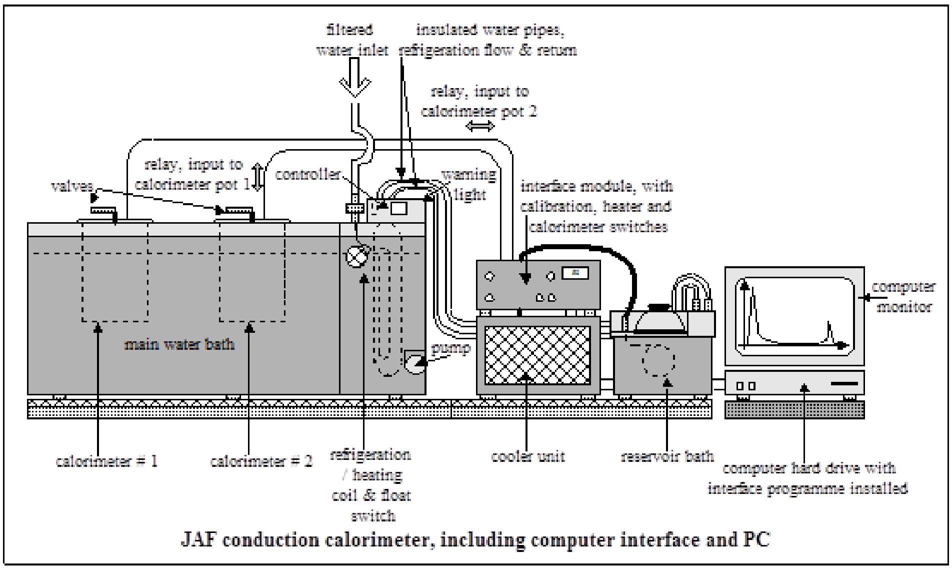
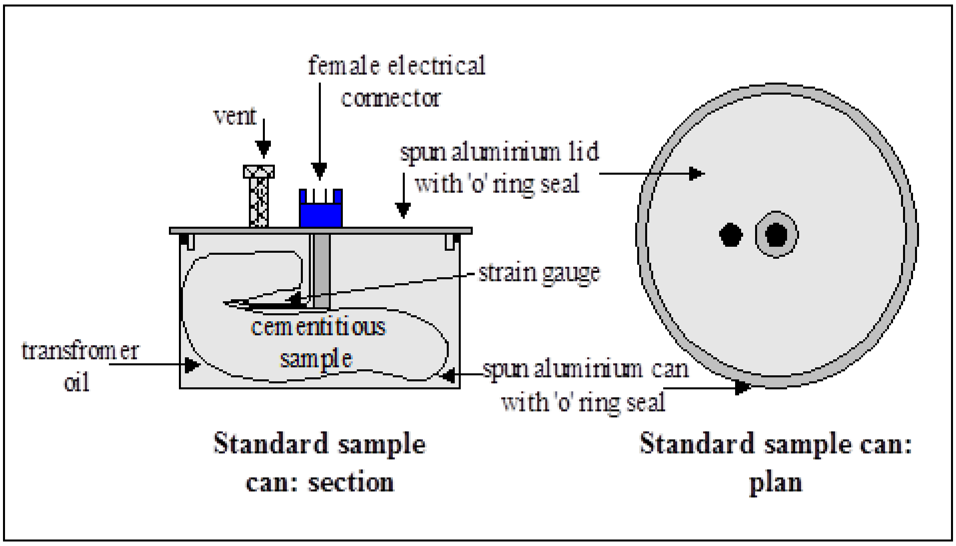


Figure 4-2 JAF isothermal conduction calorimeter full system (Forster, 2002)

The test procedure was as follows:

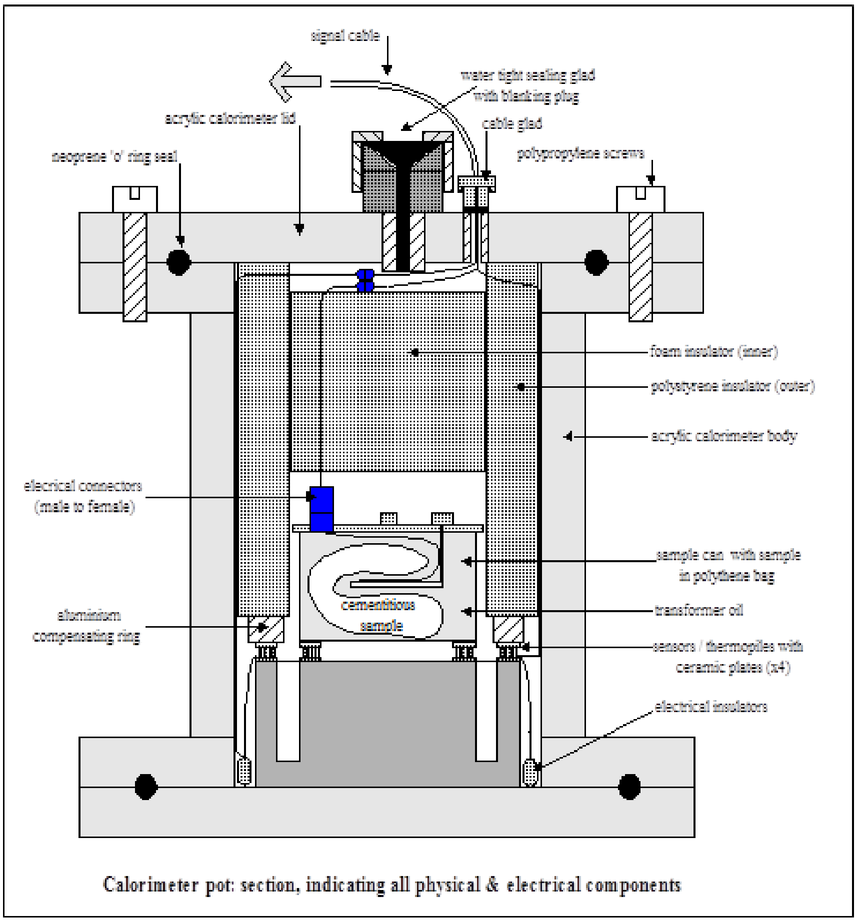
1. 30g of sample (powder) was weighed out and placed in a standard polythene bag.
2. The required amount of water was weighed out (in this case 12g of water was used as to obtain a water/powder ratio of 0.4) and poured over the powder in the polythene bag ensuring that the whole sample is fully wetted
3. The excess air was removed and the polythene bag sealed (by tying a tight knot) and placed in a small pot, containing the conducting fluid (transformer oil) and thermostat, and sealed (Figure 4-3 (a))
4. The small pot was then placed into a main pot. The outer space around the small pot was insulated with polystyrene and the top with foam to prevent heat loss (Figure 4-3 (b))
5. All the wires were connected and the main pot was placed in a water bath (maintained at 20°C) in the conduction calorimeter
6. The programme was then started and data logged. The programme measured the heat output every 6 minutes for 72 hours, calibrated the data and produced the required outputs.



Standard sample can: section

Standard sample can: plan

(a)



(b)

Figure 4-3 Two stages of the sample preparation showing (a) small pot set-up and (b) main pot set-up (Forster, 2002)

This method is commonly used because it is simple and of adequate precision for study of cement hydration. In this apparatus the heat flow from the sample pot to the heat sink (caused by the increase in temperature of sample pot due to the hydration reaction) is recorded using heat sensors where the output result is electrical impulses (in millivolts) which is then converted to kJ/kg or W/kg using the Tian-Calvet equation (calibrated), this is monitored and logged for further analysis. All this was done with the aid of a computer programme at Heriot-Watt University. The principles of the method and the supporting formulas are explained in Appendix 3 (Forrester, 1970; Wexham Developments, 1998).

The sample is prepared externally and then placed in the conduction calorimeter which takes about 15-20 minutes. Also the sample temperature has to stabilise relative to the surrounding temperature after the main pot has been placed in the water bath which takes another 20 minutes, hence overall it is not possible to record temperatures changes during the first 40 minutes of hydration.

4.2.2 Test on aggregates

Four different tests were performed on the aggregates i.e. particle density and water absorption tests, moisture content test, bulk density test and sieve analysis test. These are further explained below.

4.2.2.1 Particle density and water absorption test

The particle density and water absorption of the aggregates were obtained using a slightly modified method from BS EN 1097-6 (2000). The aggregates were initially immersed in water for 24 hours to assure full saturation. A certain mass (varying) of the aggregate was then placed in a cylindrical glass container, which was filled completely with water (ensuring no air bubbles), and weighed (W_2). After this, the aggregate sample in the container was placed in a dish, the fine aggregate was carefully dried by means of a hair dryer whereas the excess surface water on the coarse aggregates were dried using damp paper towels, until it was in a saturated surface dry state (SSD) (only the surface was dry) and was weighed (W_1). Finally the saturated surface dry aggregate sample was place in the oven for a further 24 hours to dry completely and weighed (W_4). Knowing the weight of the container only filled with water (W_3), the particle density (saturated surface dry state) and water absorption of the aggregate was calculated using the formulas below.

$$\text{Water absorption (\%)} = \frac{(W_1 - W_4)}{W_4} \times 100$$ Equation 4-1

$$\text{Particle Density} = \rho_{sat} = \frac{W_1}{W_1 - (W_2 - W_3)}$$ Equation 4-2

4.2.2.2 Moisture content test

To avoid rapid loss of consistence after mixing from absorption of water by the aggregates, the aggregates in the laboratory were always kept at a moisture level higher than the SSD state. The moisture content of the aggregates was therefore measured each time prior to batching of mortar or concrete mixes to control the total water content of the mix thus avoiding random changes in the consistency of the concrete. The test was slightly modified from that stated in BS 812-109 (1990), in this project the mass of specimens were around 200g for both fine and coarse aggregates whereas the standard specifies the minimum test weight for 0/4mm, 4/10mm and 10/20mm as 0.5, 1 and 2 kg respectively. Around 200g of wet aggregate was weighed (W_1) and dried using a microwave oven. Fine aggregates (0/4mm) were dried for 8 minutes and two grades of coarse aggregates (4/10mm and 10/20mm) were dried for 6 minutes and then weighed (W_2). The moisture content of the aggregate was then calculated using:

$$\text{Moisture content } (\%) = \frac{(W_1 - W_2)}{W_2} \times 100 \qquad \text{Equation 4-3}$$

4.2.2.3 Bulk density test

The bulk density of the aggregates was measured using a slightly modified method than in BS EN 1097-3 (1998), a 9 litre container was used for the coarse aggregates instead of a 10 litre container as specified. The aggregates were dried in an oven for 24 hours and then containers of known volume (V) (7 litres for fine aggregate and 4/10mm and 9 litres for 10/20mm coarse aggregate) were filled with the oven-dried aggregates and weighed (W_1). The weight of the empty containers were also measured (W_2) and the bulk density was then calculated using the equation below. For the fine aggregate the loose bulk density was calculated (no compaction) and for the coarse aggregates 4/10mm and 10/20mm the compacted bulk density was calculated (compacting the aggregates in three layers with 30 and 40 blows respectively).

$$\text{Bulk density} = \frac{(W_1 - W_2)}{V} \qquad \text{Equation 4-4}$$

4.2.2.4 Sieve analysis test

The sieve analysis test was done to obtain the particle size distribution of the aggregates. The test used a method slightly modified from that in BS EN 933-1 (2012). The weight of coarse aggregate sieved was about 2 kg instead of the specified 4 kg. The aggregates were placed in an oven and dried over a 24 hour period. About 2 kg of the oven-dried aggregate was placed in sieves having various sizes which were stacked on top of one another in increasing perforation size order. For the fine aggregate, the sieves were shaken for 6 minutes using a sieve shaker to ensure the sample was able to fall through the various sieves and no blockage was caused by the larger particle sizes blocking the smaller particles from passing through. The coarse aggregates, due to their larger particle size, were shaken by hand. The residue on each sieve was weighed and the cumulative percentage passing was calculated.

4.3 Tests on fresh paste, mortar and concrete

In this section the tests on fresh paste, mortar and concrete are described. These included the spread test for all fresh paste and mortar mixes and the V-funnel test for the SCC mortars. Tests performed on the fresh concrete mixes varied depending on the type of concrete:

- For the SCC mixes, the slump flow, V-funnel, J-ring and sieve segregation tests were performed
- For FC mixes, the conventional slump and the flow table tests were performed
- For the UWC mixes, as with the FC mixes, the conventional slump and the flow table tests were performed in addition to the plunge test which was used to determine the washout resistance.

The fresh mortar and concrete were considered to behave as Bingham fluids; hence in addition to the test mentioned above, rheological tests were also performed on all fresh mortar and concrete mixes.

4.3.1 Tests on fresh paste and mortar

4.3.1.1 Rheological test

As the flow behaviour of fresh paste and mortar resembles that of Bingham fluids (Figure 4-4), two-point tests were done in order to measure their yield stress (τ_o) (force required to start the flow) and plastic viscosity (μ) (resistance to flow once flow has started). Tests on pastes and mortars was performed using the Rheomat Rheometer 115 (Figure 4-5) developed by Jin (2002) for a previous work at UCL. This is a reduced scale version of the modified Tattersall two-point test used for concrete mixes.

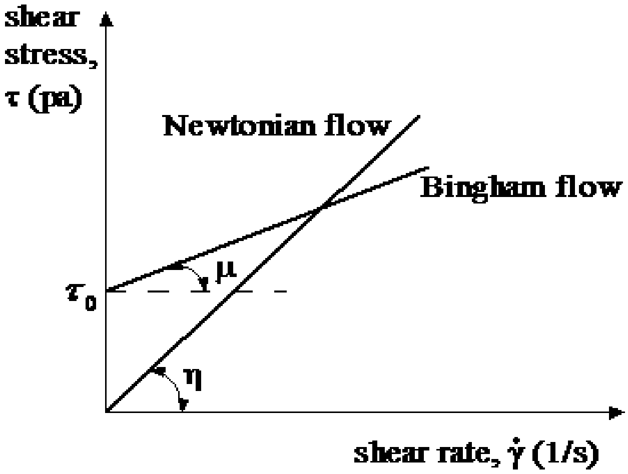


Figure 4-4 Newtonian and Bingham flow behaviours

Figure 4-5 Rheomat Rheometer 115 apparatus

The apparatus measures the torque produced by rotating a helical impeller (Figure 4-6) at various speeds in a cup filled with the mortar sample. The cup used was 92mm in diameter and the gap between the cup wall and impeller was 24mm. The speed of the impeller gradually increases to maximum and then decreases back to zero. The speed and torque values are measured and recorded by a computer which is connected to the Rheometer from which linear results are selected and a graph of torque vs. impeller speed is plotted. An analysis programme, written specifically for use with this apparatus, calculates the values of shear stress and shear rate using the intercept (g) and the gradient (h) of the plotted graph and consequently the values of yield stress and plastic viscosity respectively. The values of g and h are related to the fundamental Bingham constants by:

$$\tau_o = (K/G)g \qquad \text{Equation 4-5}$$

$$\mu = (1/G)h \qquad \text{Equation 4-6}$$

where K and G are apparatus constants

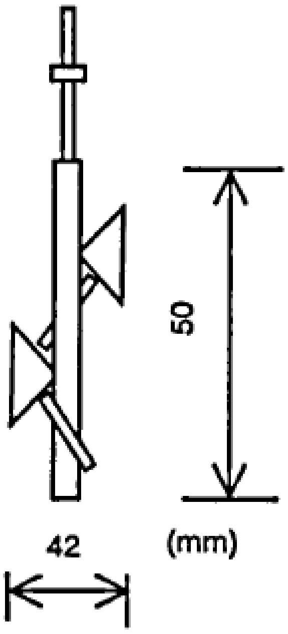


Figure 4-6 Schematic of the helical impeller for Rheomat Rheometer 115

Jin (2002) calibrated the two-point test apparatus to obtain the values of constants K and G enabling the values of yield stress and plastic viscosity to be calculated from the torque/speed (T/N) graph. The value of G was determined by testing Newtonian fluids (glycerol at various dilutions) where the viscosity (η) was known or could be measured using a concentric cylinder system and using:

$$G = 1/\eta \times T/N$$

Equation 4-7

The value of K was determined by testing a pseudo-plastic material (Welan Gum solutions at various dosages) in a concentric cylinder rheometer and in the two-point test with helical impeller and using:

$$K = (P/rG)^{(1/(s-1))}$$

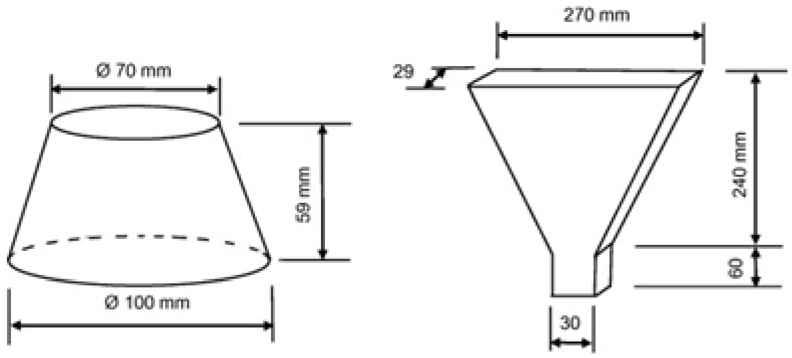
Equation 4-8

where P is a constant from the two point test and r and s are constants from the test on the pseudo-plastic material using the concentric cylinder rheometer.

Jin also looked at the significance of various containers with different geometries (different inner surface roughness and diameters) on the values of shear stress and shear rate. This was mainly to examine slippage (the wall-effect) between the mortar and the wall of the cup.

4.3.1.2 Spread and V-funnel tests

The spread test apparatus compromises of a cone (shown in Figure 4-7 (a)) and a glass plate. At the start of every test, the surfaces of the cone and the glass plate were cleaned and kept in a just-moist state. The cone was then placed on the centre of glass plate, filled with the sample (paste or mortar) and then lifted vertically. After the sample stopped flowing, the diameters of the deformed sample in two perpendicular directions were measured and an average was taken. If a ‘halo’ was visible at the perimeter of the spread, that was also measured and recorded.



(a) (b)

Figure 4-7 (a) Spread cone and (b) V-funnel apparatus for mortar mixes

For SCC mortar mixes, in addition to the spread test, the V-funnel test (Figure 4-7 (b)) was also performed. The V-funnel was placed standing upright on a level ground with the trap door at the funnel’s exit closed and was then filled with the mortar sample. The trap door was then opened to allow the concrete to flow out under gravity and a timer started. The time taken for the sample to flow out i.e. when light could first be seen when looking down through the funnel was recorded. The test was repeated three times with the same sample, the first reading was discarded and the V-funnel time recorded was the average of the second and third readings because the V-funnel surface was cleaned and just-moist at the start of the test but was not cleaned again for the repeat tests therefore was covered with mortar for the second and third readings hence the latter two have the same surface condition.

4.3.2 Tests on fresh self-compacting concrete

This section gives a brief description of the tests performed on fresh SCC mixes which included the slump flow, V-funnel, J-ring and sieve segregation tests in addition to the modified Tattersall two-point workability test.

4.3.2.1 Slump-flow test

The slump-flow test was carried out in accordance with BS EN 12350-8 (2010) where the measured total spread and the time taken for the concrete to reach a 500mm diameter (T_{500}) to assess the filling ability and the rate of flow respectively. In this test, a truncated cone (Abrams cone) was placed on a base plate (Figure 4-8) (both cleaned and in a just-moist state), filled with concrete and the cone was lifted vertically allowing the concrete to flow freely. Once the flow had ceased, two measurements were taken to the nearest 5mm i.e. the maximum and the perpendicular flow diameter, and the slump-flow value was taken as the mean of these two values. As this test was carried out by only a single operator, it was difficult to lift the slump cone and start a stop watch at the same time for measuring the T_{500}, hence throughout this project only the final spread value of the concrete was recorded.

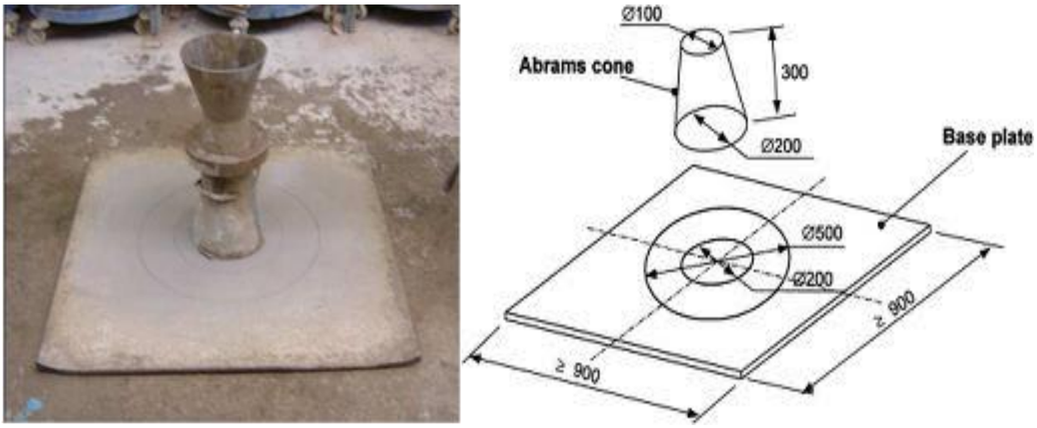


Figure 4-8 Slump-flow test apparatus for SCC

4.3.2.2 V-funnel test

The V-funnel test was carried out in accordance with BS EN 12350-9 (2010) and assesses the passing ability of the SCC flowing through a restricted area. The apparatus used is shown in Figure 4-9. The test method was similar to that of the mortar V-funnel test (4.3.1.2), as the mortar test apparatus is a small scale version of this apparatus used for concrete. Similarly the V-funnel time was taken as the average between the second and third readings of a set of three.

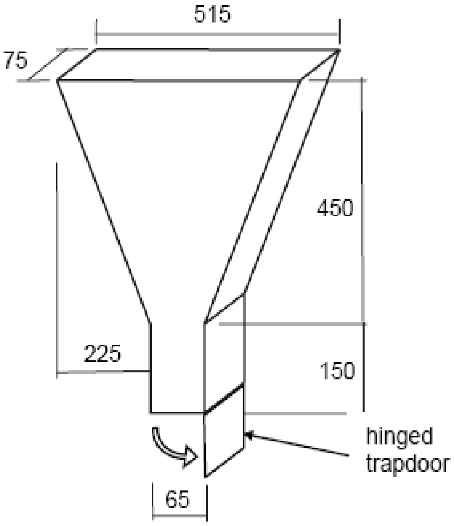


Figure 4-9 V-funnel test apparatus for SCC

4.3.2.3 J-ring test

This test investigates the blocking behaviour of SCC by simulating flow through reinforcing bars, which is the case on real construction sites, giving an indication of the passing ability of the concrete. The apparatus shown in Figure 4-10 is a 300mm diameter circular steel ring having 16 smooth steel bars of 18mm diameter with equal spacing of 41mm around the circumference. The test was carried out in accordance with BS EN 12350-12 (2010). The Abrams cone, used in the slump flow test (4.3.2.1), was placed centrally inside the J-ring. As with the other tests, the test equipment was cleaned and in a just-moist state before the start of every test. The cone was then filled with concrete and lifted vertically allowing the concrete to flow freely. When the concrete had stopped flowing, heights between the concrete surface and the top of the J-ring was measured to the nearest 1mm, one in the centre of the J-ring (highest point of the concrete) and two measurements just outside the J-ring on either side. This was done in two directions (perpendicular) and the step height recorded was the average difference between the central height and the outer height measurements.

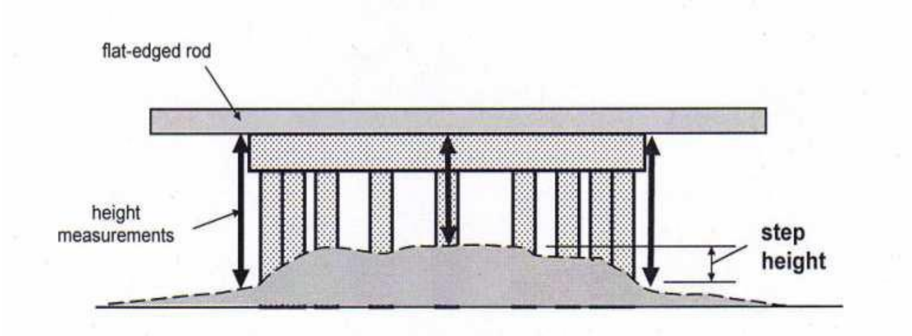


Figure 4-10 J-ring test apparatus for SCC

4.3.2.4 Sieve segregation test

Segregation resistance is the ability of a fresh mix to maintain its original, adequately uniform distribution of constituent materials. This test measures the resistance of SCC to segregation and was carried out in accordance with BS EN 12350-11 (2010). The test apparatus is shown in Figure 4-11.

Figure 4-11 Sieve segregation test apparatus for SCC

About 10 litres of concrete was poured into a bucket, covered to prevent moisture loss and left to settle for about 15 minutes. Then a sample of 4.8±0.2 kg of the concrete was poured from a height of 500mm onto a sieve (with 5mm perforations) (M_c) and left for 2 minutes to allow any laitance to pass through (M_l). The segregation index was calculated as the percentage of weight of laitance relative to the weight of poured sample using the formula below.

$$\text{Segregation index (\%)} = \frac{M_l}{M_c} \times 100 \qquad \text{Equation 4-9}$$

4.3.2.5 Modified Tattersall two-point workability test

This test was used to determine the Bingham constants τ_o (yield stress) and μ (plastic viscosity). The general arrangement of the apparatus is show in Figure 4-12.

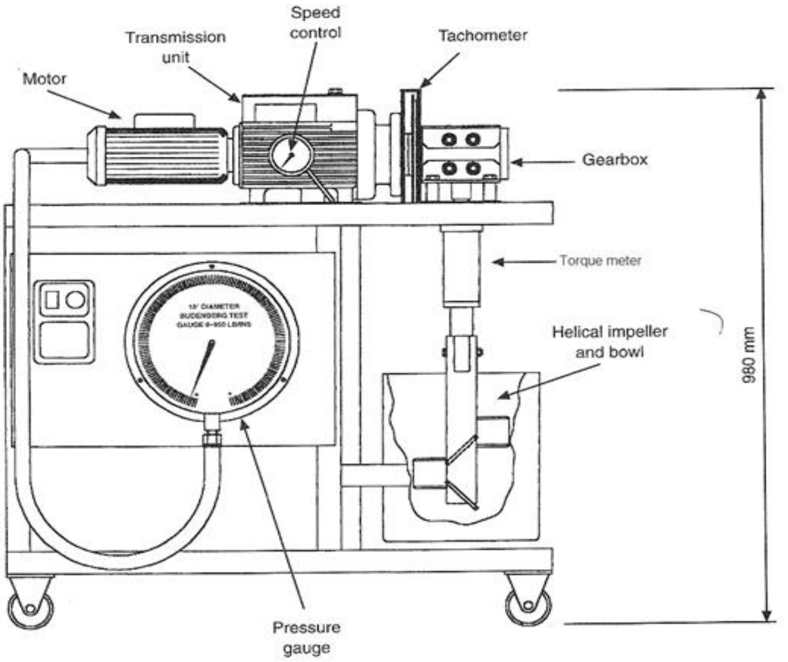


Figure 4-12 Modified Tattersall two-point test apparatus (Domone et al., 1999)

Initially the bowl was filled with concrete. The impeller speed was quickly increased to mark 6 (which is equal to approximately 82 rev/m) and reduced to zero in increments of 1. A Torque meter was used to record both the speed of the impeller and the resultant torque. In the original version of the apparatus, the torque was obtained from its relationship with the oil pressure but this was inaccurate and slightly tedious since the oil pressure oscillated widely hence an average value had to be estimated. As with the mortar two-point test described in 4.3.1.1, a graph of torque vs. impeller speed was plotted and the gradient (h) and intercept (g) were determined. The device had been previously calibrated such that the yield stress (τ_o) is equal to 122 times the intercept (g) and the plastic viscosity (µ) is equal to 17.24 times the gradient (h) (Domone et al., 1999), hence the Bingham constants were calculated from the torque/speed graph.

4.3.3 Tests on fresh flowing concrete

The tests performed on fresh FC mixes included the conventional slump test, the flow table test, and similar to the SCC, the modified Tattersall two-point workability test. In addition to slump, the spread i.e. slump flow was also measured.

In this section a brief description of only the first two tests is given as the two-point test was described in 4.3.2.5.

4.3.3.1 Conventional slump test

The apparatus used in this test was the same as that in the slump flow test (4.3.2.1), and similarly, this test gives an indication of the mix consistency. The test was done in accordance with BS EN 12350-2 (2009).

4.3.3.2 Flow table test

This test was carried out in accordance with BS EN 12350-5 (2009).

4.3.4 Tests on fresh underwater concrete

As with fresh flowing concrete, the conventional slump, flow table and two-point tests were also performed on all fresh underwater concrete mixes. Similarly the slump flow was also measured during the slump test. In addition to these tests, the plunge test was also performed on the mixes to assess the washout resistance which is one of the key properties of UWC.

4.3.4.1 Plunge test

The plunge test was carried out using a slightly modified method than that in the CRD C61 (1989) standard which was adopted by the US Corps of Engineers. The apparatus used is shown in Figure 4-13. In the standard test procedure, the washout is measured by determining the relative amount of cement paste and mortar lost when the concrete sample, placed in a perforated basket (3mm perforations), is passed through or “plunged” in the water. Initially a mass of concrete in excess of 2 kg is placed in the perforated basket, sample tamped 10 times and the sides of the basket tapped 10-15 times with a rod and the extruded concrete cleaned off the sides of the basket, after which the mass of the concrete sample is determined (should be 2±0.2 kg) and then is allowed to freely drop three times through 1.7m of water. The change in mass of the sample is measured and the washout expressed as a percentage loss of mass relative to the initial weight.

As mentioned in 2.2.2.3, previous work concluded that obtaining an accurate washout resistance with this test was not possible due to the fact that the aggregates in the mix could block the perforations around the basket preventing washout hence resulting in a low washout (Annett, 1987; Sonebi et al., 1999). Hence the test procedure used in this project was slightly different, it was decided to increase the size of the perforations on the mesh basket to 10mm instead of 3mm allowing larger aggregates i.e. 4/10mm coarse aggregate to also flow out reducing the chances of blockage hence obtaining a more realistic washout value. The pipe used had a height of only 1m instead of the specified 1.7m hence to compensate for the shorter drop height the number of drops was increased from three to five. Apart from these differences, all other steps were done according to the standard.

Figure 4-13 Plunge test apparatus for UWC

4.4 Tests on hardened concrete

The three types of concrete, SCC, FC and UWC exhibit different fresh property characteristics from one another and also from normally vibrated concrete hence required different testing methods for different concrete types. However the hardened properties of all these different concrete types are assessed in the same way as they all depend on the same factors such as cement hydration, water/cement ratio and powder types and combinations used. Existing test methods were used to assess the hardened properties of the concrete mixes and are described briefly below.

4.4.1 Casting and curing

Casting and curing of the concrete specimens was mainly based on BS EN 12390-2 (2009) with some modifications depending on the type of concrete being cast. For the SCC, there was no compaction during casting. For the FC mixes, to achieve full compaction but avoid over-compaction leading to segregation, the concrete was compacted in two layers using a tamping rod (5 tamps per layer) instead of using the vibrating table. Finally for the UWC mixes, the same procedure was followed as with FC, with the primary test specimens cast in air, in addition 6 cubes (2 sets of 3) were cast underwater with the concrete being poured through a plastic tube, replicating the tremie casting method, with the tip of the tube being submerged in the concrete at all times.

For the SCC and FC mixes, 27 cubes (100x100x100 mm^3) with 18 cubes for the UPV and the compressive strength test and 9 cubes for the sorptivity test, 7 cylinders (100mm diameter and 200mm in length) with 6 for the tensile splitting test and one for the RCPT and 2 prisms (100x100x500 mm^3) for the dynamic modulus test were cast from a single batch of concrete. For the UWC, a total of 30 cubes were cast with 6 having being cast underwater along with the 7 cylinders and 2 prisms as with SCC and FC mixes.

All the specimens were covered over with plastic sheets and stored in the laboratory for about 24 hours after which they were demoulded, marked and placed in a curing tank in water at 20°C until the testing date. All the tests results reported were an average of three specimens tested except for the dynamic modulus test (average of two specimens) and the RCPT (single specimen tested). The tests were carried out at various ages from 1 to 91 days. The density of each specimen was determined before each test, except for the RCPT specimens.

4.4.2 Density test

The density of each specimen i.e. cubes, cylinders and prisms, was determined using Archimedes principle of buoyancy and the test was carried out in accordance with BS EN 12390-7 (2009). The weight of the specimen was measured in air (M_a) and in water (M_w), knowing the density of water (ρ_w), the density of the concrete (ρ) was calculated by:

$$\text{Density of concrete } (\rho) = \frac{M_a}{(M_a - M_w)} \times \rho_w \qquad \text{Equation 4-10}$$

4.4.3 Strength tests

The strength tests included the compressive strength test on cube specimens and the indirect tensile splitting tests on cylinder specimens. These tests are briefly explained below.

4.4.3.1 Compressive strength test

The compressive strength test was carried out according to BS EN 12390-3 (2009). Each test set involved testing three 100mm cube specimens; this was carried out at ages 1, 3, 7, 28, 56 and 91 days for SCC and FC and for UWC the same pattern was followed apart from the test at 1 day which was not done. The test apparatus is shown in Figure 4-14.

Figure 4-14 Uniaxial compression test machine

4.4.3.2 Tensile splitting strength test

The tensile strength, which is an indication of the crack resistance, of the concrete was measured indirectly using the tensile splitting strength test as direct tensile tests are difficult to conduct on concrete specimens. The test procedure followed was in accordance with BS EN 12390-6 (2009). Three cylinder specimens were tested per mix at ages of 28 and 91 days.

4.4.4 Non-destructive tests

Two of such tests have been carried out in this project, the ultrasonic pulse velocity (UPV) and the dynamic elastic modulus test. These tests are further explained below.

4.4.4.1 Ultrasonic pulse velocity (UPV) test

The UPV test was carried out according to BS EN 12504-4 (2004). The apparatus, known as the Pundit, used in this test is show in Figure 4-15. The UPV test was performed on cubes (sets of 3) at ages 1, 3, 7, 28, 56 and 91 days just before the cube compression test was done.

Figure 4-15 The Pundit apparatus

4.4.4.2 Dynamic elastic modulus test

This test was used to measure the resonant frequency of vibration of a concrete prism specimen in the longitudinal direction whilst supported at mid-span. The Erudite apparatus (shown in Figure 4-16) was used to carry out this test in accordance with BS 1881-209 (1990). Having measured the resonant frequency (n) in Hz, length (l) in mm and density (ρ) in kg/m^3 of the concrete prism, the dynamic elastic modulus (in GPa) was calculated using:

$$\text{Dynamic elastic modulus } (E_d) = 4n^2l^2\rho \, x \, 10^{-15} \quad \text{Equation 4-11}$$

Figure 4-16 The Erudite apparatus

As with the compression and the UPV tests, the dynamic elastic modulus was measured at ages 1, 3, 7, 28, 56 and 91 days. As the test was non-destructive, the prisms were transferred back to the curing tanks after the completing of the test and the same two prisms were used at all ages.

4.4.5 Durability tests

In this project, two durability test were performed, the sorptivity test and the rapid chloride penetration test (RCPT) which are simple, relatively quick and convenient tests.

4.4.5.1 Sorptivity test

This test was done to assess the resistance of water movement through the concrete by capillary suction. The procedure followed in this test is that developed by Liu (2010) in a previous study at UCL, a slightly modified version of the RILEM TC 116-PCD (1999). The test method was as follows:

1. A set of three 100mm cubes were selected for water absorption tests after 7, 28 and 91 days curing under water.
2. After the specimens were removed from the water, they were placed in an oven at 55 °C for 21 days. This temperature was chosen to prevent micro-

cracking and, thus prevent unrealistically high sorption results. Based on preliminary testing, Liu (2010) reported that approximately half of the weight loss occurred within 4 days and the weight of specimens was found to be stable after 20 days.

3. After their removal from the oven, the specimens were allowed to cool to room temperature for 24 hours.
4. Only one surface of the concrete needed to be in contact with the water and a side surface was chosen in order to eliminate any surface finishing effects which could lead to abnormally high sorption results. The opposite surface was exposed to air and the other four surfaces were sealed by an epoxy resin, ensuring unidirectional flow of water through the concrete specimen. Then the specimens were stored in the conditioning room at 20 °C and 90% relative humidity for another 24 hours to achieve a constant of saturation.
5. All specimens were placed on a sponge, which was completely immersed in water (as shown in Figure 4-17). A water layer of about 3 mm was maintained throughout the test, additional water was added if necessary. All the specimens were placed in a tray which was covered with a plastic sheet and kept in the conditioning room to avoid moisture loss.
6. The initial weight of the specimens was measured before contact with water. Specimens were removed and weighed approximately every 15 minutes in the first four hours and then once a day (if possible) for 20 days.

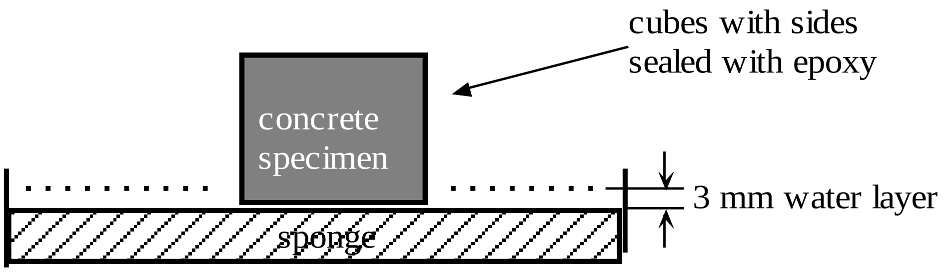


Figure 4-17 Schematic diagram of the sorptivity test (Liu, 2010)

According to Neithalath (2006) and Zhu and Bartos (2003), there is a linear relationship between the water intake per unit area with square root of time over the first 4 hours of water immersion given by:

$$\frac{M}{A} = S_1 t^{\frac{1}{2}} + \bar{S}_1 \qquad \text{(Short-term)} \qquad \text{Equation 4-12}$$

where M is the mass of water intake, A is the cross-sectional area, S is the sorptivity coefficient and $\bar{S}_1$ is a correction term.

Hence the sorptivity coefficient (short term) was obtained by linear regression of water intake per unit area vs. square root of time for the first four hours period.

As for the long term sorptivity coefficient, Liu (2010) noticed that when plotting the data over the whole 21 days, the trend between water intake per unit area and square root of time was close to a logarithmic relationship. The long-term sorptivity coefficient was therefore obtained by logarithmic regression of water intake per unit area vs. square root of time for the entire 21 day given by:

$$\frac{M}{A} = S_2 \ln(t^{\frac{1}{2}}) + \bar{S}_2 \qquad \text{(Long-term)} \qquad \text{Equation 4-13}$$

However the measured long-term sorptivity coefficients did not seem to add any further understanding to that obtained from the 4-hour (short-term) values, hence for the purpose of this research it was decided not to discuss this further and only use the short-term sorptivity coefficients for the purpose of comparison.

4.4.5.2 Rapid chloride penetration test

This test was performed according to ASTM C1202 (2007).

1. The test method involved obtaining a 100 mm diameter 50 mm thick cylinder sample of the concrete being tested.
2. The side of the cylindrical specimen was coated with epoxy, and allowed to dry overnight.
3. It was then placed in a vacuum chamber for 3 hours and then vacuum saturated for further hour (with water poured over specimen without stopping the vacuum) and then allowed to soak for 18 hours.

4. It was then placed in the test device (apparatus shown in Figure 4-18). The left-hand side (–) of the test cell was filled with a 3% sodium chloride (NaCl) solution (equivalent to 30g NaCl per litre of water). The right-hand side (+) of the test cell was filled with 0.3N sodium hydroxide (NaOH) solution (equivalent to 12g NaOH per litre of water).
5. The system was then connected to the power supply and a 60-volt potential was applied for 6 hours. A data logging programme (Agilent VEE) was used to obtain and record the data. These were taken continuously and a graph of current vs. time was plotted. At the end of 6 hours the sample was removed from the cell and the amount of coulombs passed through the specimen was calculated from the area under the graph.

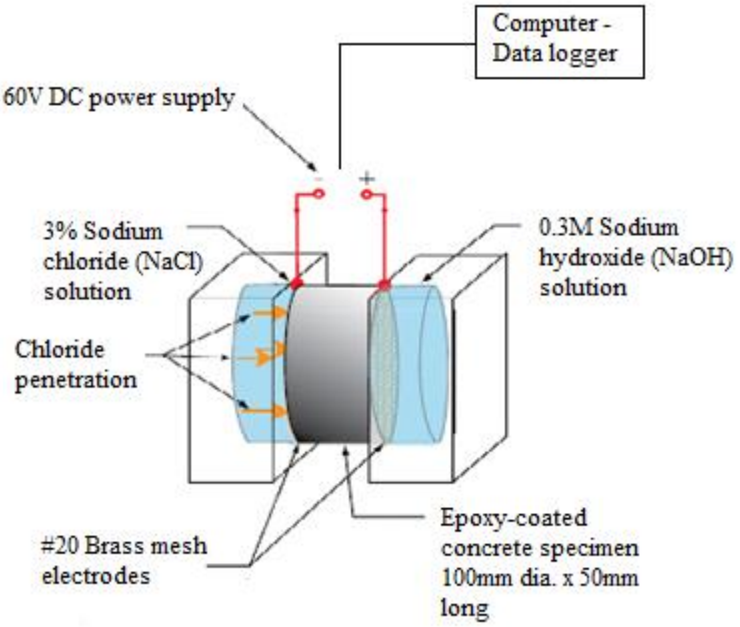


Figure 4-18 Schematic diagram of the RCPT setup (American Concrete Institute, 2006)

As only one acrylic test rig (manufactured in the workshop at UCL) was available (shown in Figure 4-19), only one specimen could be tested at any one time. Therefore only one cylinder (100mm diameter, 200mm in length) was cast per mix for this test, which was then cut longitudinally into three 50mm thick specimens with the top and bottom 25 mm thick concrete discarded. This test was performed at ages 7, 28 and 91 days with one specimen being tested at each age.

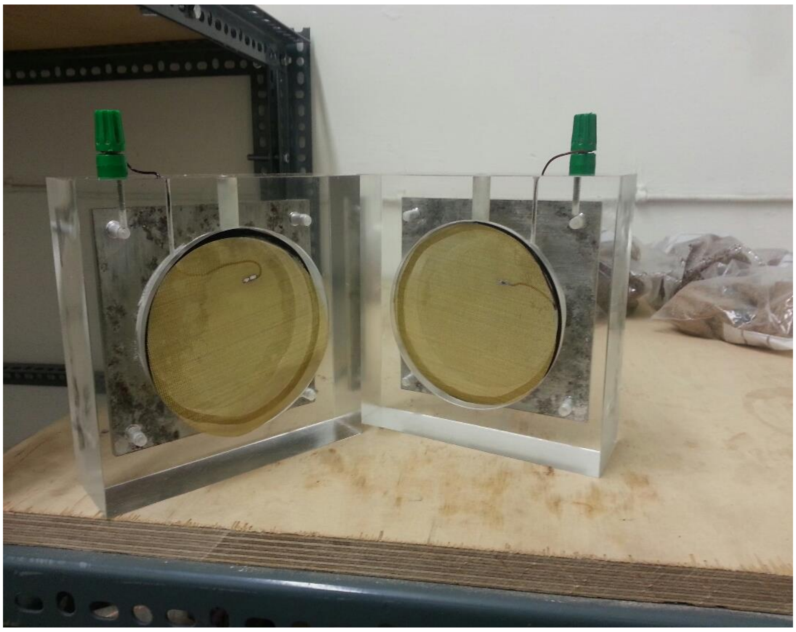


Figure 4-19 RCPT test rig manufactured at UCL

4.5 *Precision of tests*

Almost all tests and measurements carried out by any person are bound to have various sources of errors, with the tests in this project being no exception. Therefore in order to be able to properly interpret the results, one needs to be aware of the possible errors which these tests can produce. The accuracy of these tests can be evaluated by repeatability and reproducibility, which are statistical measures of the errors within test methods.

According to BS ISO 21748 (2010), the definitions of these two values are:

Repeatability (r) is defined as the difference between two consecutive test results, performed by the same operator, using the same test method and apparatus, in the same laboratory and environment that should be exceeded only once in 20 times.

Reproducibility (R) is defined as the difference between two consecutive test results, performed by a different operator with different apparatus in a different laboratory and environment, using the same test method, which should be exceeded only one in 20 times.

For a 95% confidence level, the values of repeatability and reproducibility are obtained by multiplying their standard deviations, S_r and S_R respectively, by a factor of 2.8 such that:

$$r = 2.8S_r \qquad \text{Equation 4-14}$$

$$R = 2.8S_R \qquad \text{Equation 4-15}$$

Note: the factor is obtained by multiplying 1.96 (95% confidence level) x $\sqrt{2}$ (two results)

Hence the maximum difference between any two of 20 measurements by the same operator should not be less than r, and that by different operators should not be less than R. With concrete it is very difficult to achieve the standard requirements needed for repeatability and reproducibility, as it is a variable material, its constituent materials are also variable and its properties change with time. Also the specimens have inherent variability. As all the tests in this project were performed by a single operator, with the same apparatus in the same lab environment, it was possible to fulfil many of the repeatability requirements. The precisions of various tests have been evaluated through major experimental programmes and are given in their respective standards. The data for the tests used in this project are shown in Table 4-1.

Table 4-1 Repeatability and reproducibility values for various tests

Tests	Classes		Standard deviation		Repeatability	Reproducibility
SCC			S_r	S_R	r	R
Slump flow test	Slump flow (mm)	600-750	15	15.4	42	43
V-funnel test	V-funnel time (t) (seconds)	~8s	0.8	1.1	2.1	3.1
J-ring test	Spread (mm)	600~750	16.4	16.4	46	46
	Step height (mm)	≤20	1.6	1.8	4.6	4.9
Sieve stability test	Sieve segregation (%)	≤20	1.3	1.3	3.7	3.7
FC and UWC						
Slump test	Slump (mm)	50-80	5.8	9	16	25
Flow table test	Flow (mm)	555	24.6	32.5	61	91
Compression test	Cube size (mm)	100	3.2	5.4	9	15.1
		150	3.2	4.7	9	13.2

For the SCC tests, there is no significant difference between the repeatability and reproducibility values, suggesting that the accuracy of the test results is not operator dependent. For the slump and flow table test, the reproducibility values are higher than the repeatability values signifying the accuracy is operator dependent. The slump range for which this value is valid for is 50-80 mm with no value available for the slump range achieved with FC and UWC, 200-240 mm.

As for the hardened and durability property tests, only precision data was available for the cube compression test with repeatability and reproducibility values of 9 and 15.1% (percentage of the mean of two test results) respectively. For the RCPT, according to ASTM C1202 (1993), for the same operator, the coefficient of variation of test results has been found to be 12.3%, therefore the results of two properly conducted tests by the same operator on the same concrete batch should not differ by more than 34%. For the hardened and durability tests, sets of 3 specimens were tested at each testing age as due to the inherent variability of the specimens it was possible to spot and discard any outliers (if any) and still have two valid results to report. This was the case in all tests except for the dynamic elastic modulus test, where only 2 prism specimens were tested, and for the RCPT where due to the apparatus limitations, only a single specimen was tested at each testing age. Overall it is important, when interpreting and comparing single test values to account for the repeatability, meaning that any two values with a difference of less than r might not be significantly different.

Chapter 5 Constituent Materials

In this chapter, the constituent materials used in this research are described and discussed. SCC is very sensitive to changes in properties of the materials used, mainly to the variation in the particle size distribution (PSD) of the finer sized particles i.e. fine aggregate and powders. For the fine aggregates, the percentage of particles finer that 125µm (considered as powder) for the different batches initially tested ranged between 1 – 4%, a significant range considering the sensitivity of SCC. Therefore, to eliminate the effects of variation in material properties, all the mortar and concrete mixes were batched using a single batch of fine aggregate and a single batch of the various powders. Since SCC is more sensitive to the variation in the amount of finer particles than to variation in the coarse aggregate properties, it was assumed that various batches of coarse aggregate were nominally consistent and had the same properties. Three types of limestone powder was ordered, each having different fineness, hence tests were done to determine which type to use in this research. In addition, as mentioned in 4.2.1, the heat of hydration test was carried out on various binder compositions to compare the early hydration of different powder combinations.

5.1 Aggregate

Three different classes of aggregates were used in this project, one fine aggregate 0/4mm class, and two coarse aggregate classes of 4/10mm and 10/20mm. All the aggregates were supplied by Jewson Ltd (Builders Merchants). The property of the aggregates is described below.

5.1.1 Fine aggregate

Natural uncrushed river sand, of 0/4mm class, was used as the fine aggregate. As mentioned previously, the same batch of fine aggregate was used in all mortar and concrete mixes throughout. The relative particle density was measured as being 2.6 in the saturated surface-dry (SSD) state. The water absorption of the aggregate was 1.48 %. The un-compacted bulk density was 1544 kg/m^3. The fine aggregate PSD is show in Figure 5-1.

5.1.2 Coarse aggregate

Uncrushed marine aggregates, of classes 4/10mm and 10/20mm, were used as the coarse aggregate. The relative particle densities in the SSD state, of the 4/10mm and 10/20mm were measured as 2.53 and 2.61 respectively. The water absorption was measured as 2.3% and 1.32% respectively. The compacted bulk densities of the aggregates were 1489 and 1495 kg/m^3. The PSDs of the aggregates are shown in Figure 5-1.

The coarse aggregate used in the mixes was a 1:2 combination of 4/10mm and 10/20mm aggregate respectively. This was found by Liu (2010) to give the maximum bulk density with minimum voids. The report published by the Building Research Establishment (BRE) (Teychenne et al., 1997) on design of normal concrete mixes also suggests the use 1:2 combination as a general guideline.

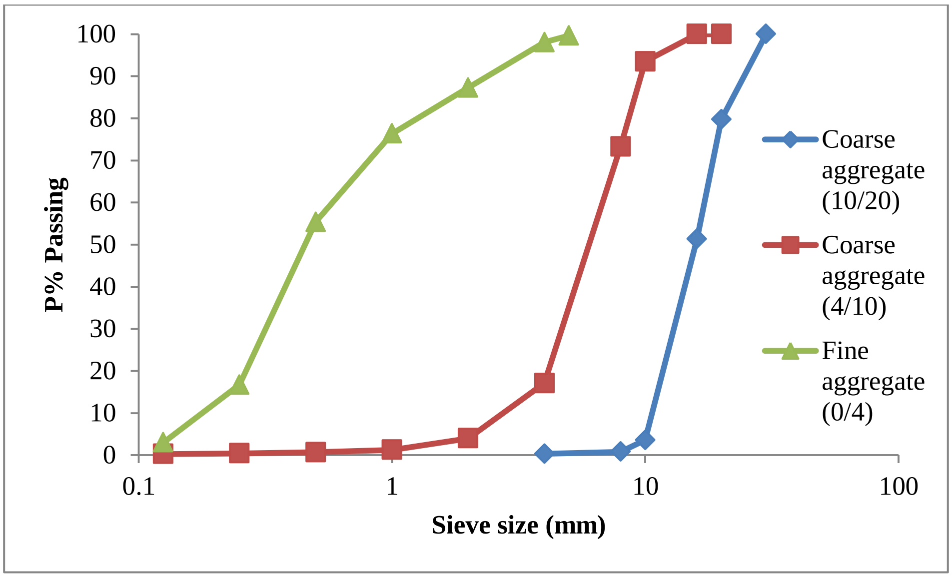


Figure 5-1 Aggregate grading curves

5.2 Powders

This section describes the various powders used in this project i.e. Portland cement, ground granulated blastfurnace slag, fly ash and limestone powder. The required quantity of each powder, for the entire test programme, was ordered as one batch to eliminate the effect of batch to batch variations.

5.2.1 Portland cement

Ordinary Portland Cement (PC) of class CEM I 52.5N was used. This cement was supplied from the Cauldon works of Lafarge Cement and conformed to BS EN 197-1 (2011). The relative density was assumed to be 3.15. The chemical compositions (given by the supplier) are shown in Table 5-1.

Table 5-1 Physical and chemical composition of PC

Chemical composition	**(%)**
SiO_2	20.43
Al_2O_3	5.4
Fe_2O_3	3.03
CaO	64.22
MgO	1.43
SO_3	3.78
K_2O	0.85
Na_2O	0.15
Eq_{Na2O}	0.71
LOI	0.6
F_{CaO}	2.4
Cl	0.025
Compound composition (Bogue)	**(%)**
C_3S	46.6
C_2S	20.3
C_3A	8.55
C_4AF	9.29
Strength	**MPa**
1 Day	25.6
2 Day	33.4
28 Day	56.4

5.2.2 Ground granulated blastfurnace slag

The ground granulated blastfurnace slag was supplied from the Purfleet works of Hanson Cement (UK), and complied with BS EN 15167-1 (2006). The relative density was given as 2.9 and its chemical composition is given in Table 5-2.

5.2.3 Fly ash

The fly ash was supplied from Fiddler’s Ferry Production Plant by RockTron, and conformed to BS EN 450-1 (2012). The relative particle density was given as 2.23

and the loss on ignition was 5.46%. The chemical composition is given in the Table 5-3.

Table 5-2 Chemical composition of ggbs

Chemical composition	(%)
SiO_2	35.39
Al_2O_3	12.93
Fe_2O_3	0.27
CaO	39.8
MgO	8.42
MnO	0.5
TiO_2	0.73
Na_2O	0.3
K_2O	0.51
Na_2O Equiv.	0.64
LOI	0.6

Table 5-3 Chemical composition of fly ash

Chemical composition	(%)
SiO_2	50
Al_2O_3	28
Fe_2O_3	7.3
CaO	2.1
MgO	1.4
K_2O	3.1
Na_2O	0.7
P_2O_5	0.3
TiO_2	1.0
MnO	0.06
Cr_2O_3	0.03
LOI	5.46

5.2.4 Limestone powder

The limestone powder used was supplied from the Dowlow production plant by Omya (UK), and conformed to BS 7979 (2001). The relative density of limestone powder was given as 2.7. The limestone powder was almost purely ground calcium carbonate ($CaCO_3$) (99% by weight) with other minor oxides. Three different batches of limestone powder (Betocarb 10, 45 and 80) were ordered, each with varying fineness (Betocarb 10 being the finest).

5.2.5 Particle size distribution of powders

The particle size distributions of all the powders are shown in Figure 5-2.

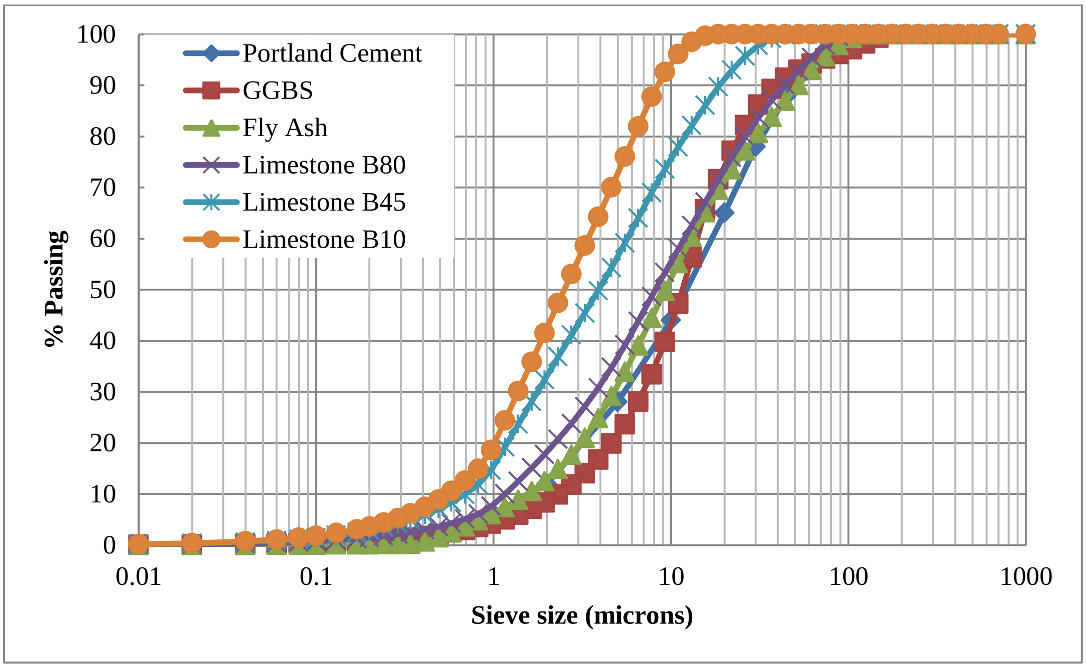


Figure 5-2 Particle size distribution of all powders used in this project (performed by Hanson (UK))

The particle size distribution of the ggbs and fly ash were very similar to but slightly finer than cement between 100µm - 10µm whilst all the limestone powder batches were fine than the cement. Hence it can be expected, when used as an addition with cement, the ggbs, fly ash and limestone powders would improve the particle packing creating a denser matrix reducing the porosity of the concrete. The specific surface area (SSA) of the cement was given as 447 m^2/kg, as no SSA data was given from the manufacturers for ggbs and fly ash, these were assumed to have similar SSA as cement and the limestone powders B80, B45 and B10 had SSA values of 480, 719 and 893 m^2/kg respectively (measured by Hanson Cement on our behalf). Since the SSA of Limestone powder B80 was similar to that of cement, with one of the key reasons for using limestone powder was to achieve better packing, it was decided not to use this in the mixes and only go ahead with using B45 and B10 limestone powders.

5.2.6 Retained water ratio and deformation coefficient of powder combinations

As to better assess the performance of the powders, a flow spread test, similar to the spread test described in 4.3.1.2, was performed on paste mixes incorporating various powder combinations with varying water content. Having measured the average flow diameter (D), the relative flow area (R_a) was then calculated using:

$$R_a = (D/100)^2 - 1$$

Equation 5-1

For a paste, the relative flow area (R_a) and the water/powder ratio by volume (V_w/V_p) are linearly related (Domone & Chai, 1997). For each powder type and combination, pastes were prepared with varying water content, the flow diameter measured and the graph of water/powder ratio vs. relative flow area plotted. The graph for pastes with various replacement levels of fly ash are shown in Figure 5-3.

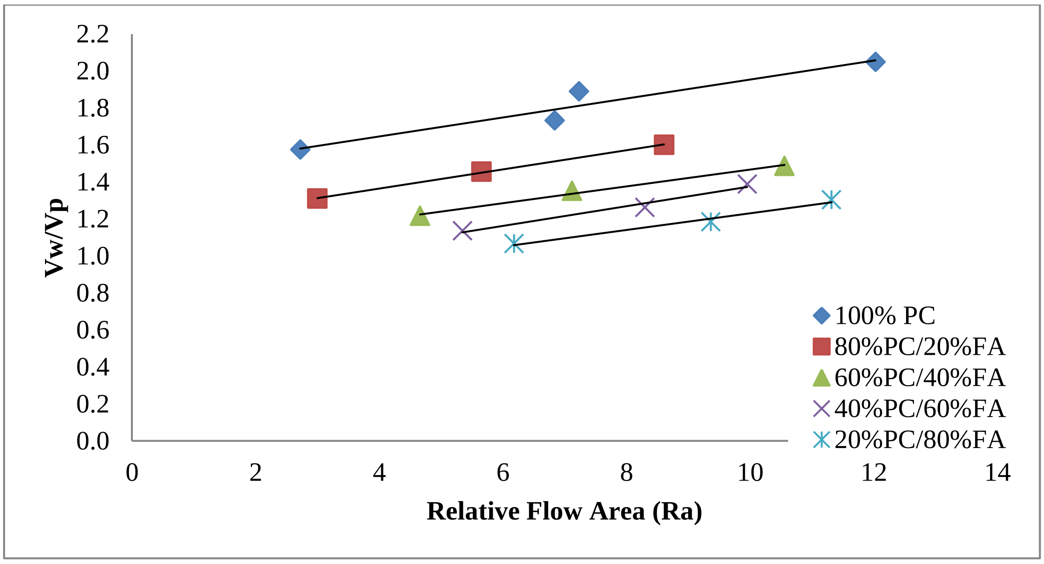


Figure 5-3 Water/powder ratio vs. relative flow area for fly ash paste

The equation of the linear relationship is

$$V_w/V_p = \beta_p + R_a.E_p$$ Equation 5-2

Where

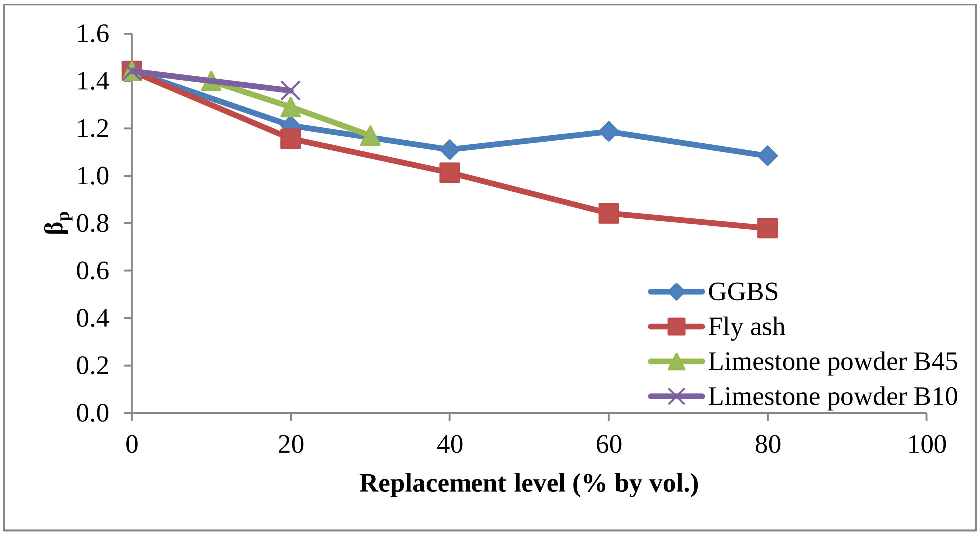
- β_p (the intercept with the V_w/V_p axis) is the retained water ratio i.e. the water required to commence flow, which includes the water adsorbed on the powder surface together with the water required to fill the voids between the powder particles. A lower value of β_p means less water to commence the flow.
- E_p, known as the deformation coefficient (slope of the line), gives an indication of the sensitivity of the paste to changes in water content (Domone & Chai, 1997). A larger value of E_p means a less sensitive paste, hence more robust mixture.

Pastes with various powder combinations were tested and the results are shown in Table 5-4.

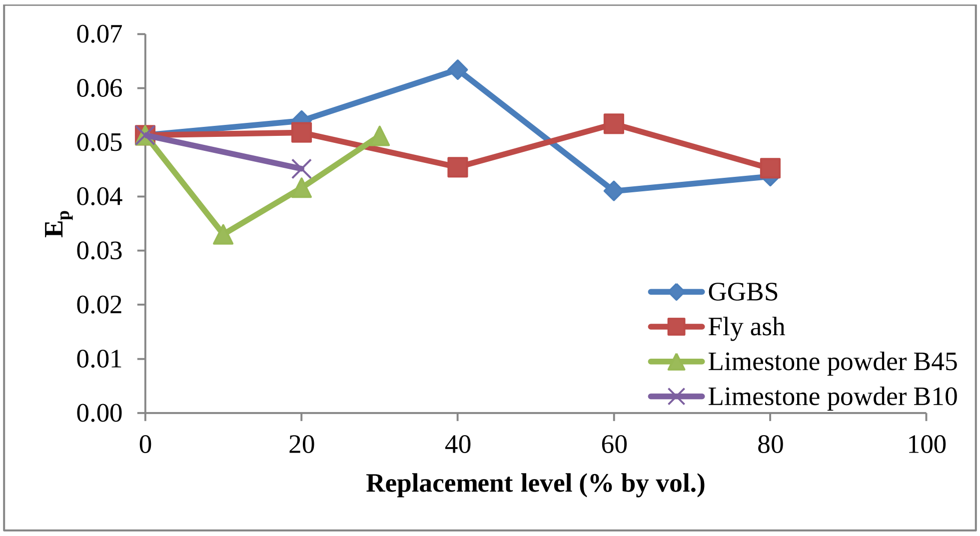
Table 5-4 Retained water ratio and deformation coefficient of powder combinations

Powder	**β_p**	**E_p**
PC	1.442	0.051
Limestone		
B45 Limestone	0.950	0.068
B10 Limestone	1.196	0.081
90% PC/10% B45	1.400	0.033
80% PC/20% B45	1.290	0.042
70% PC/30% B45	1.170	0.051
80% PC/20% B10	1.360	0.045
GGBS		
80% PC/20% GGBS	1.212	0.054
60% PC/40% GGBS	1.111	0.063
40% PC/60% GGBS	1.187	0.041
20% PC/80% GGBS	1.084	0.044
Fly Ash		
80% PC/20% FA	1.157	0.052
60% PC/40% FA	1.013	0.045
40% PC/60% FA	0.842	0.053
20% PC/80% FA	0.779	0.045

The effects of replacement level of additions in binary blend powders on the β_p and E_p are shown in Figure 5-4.



(a)



(b)

Figure 5-4 Flow spread results for powder combinations: (a) retained water ratio and (b) deformation coefficient

Looking at Figure 5-4, it can be seen that the retained water ratio values (β_p) decrease with increasing replacement levels of additions which is due to a combination of improved overall packing and physical properties of the additions. The deformation coefficients (E_p) show less clear trends and seem to only vary slightly (between 0.04 – 0.06) with increasing addition levels. With ggbs and fly ash, the value of E_p, at 40% and 20% replacement levels respectively was higher than that of the cement indicating increased robustness. With the limestone powder, the sensitivity of the mix initially increased but seemed to reduce as the replacement levels increased, with the paste with a 30% B45 limestone powder replacement having the same E_p value as cement.

Comparing the pastes with 20% limestone powder replacement level, the use of B45 or B10, both resulted in a reduction in the retained water ratio and increased mix sensitivity. As an attempt to achieve better packing, it was decided to test a combination of these two powders at combined replacement level of 20% resulting in a greater particle size distribution. The results are shown in Table 5-5.

Table 5-5 Retained water ratio and deformation coefficients of limestone powder combinations

Powder	**β_p**	**E_p**
PC	1.442	0.051
80% PC/20% B45	1.29	0.042
80% PC/20% B10	1.36	0.045
80% PC/20% Limestone powder		
75% B45/ 25% B10	1.21	0.043
50% B45/ 50% B10	1.22	0.045
25% B45/ 75% B10	1.18	0.051

The results in Table 5-5 show that combinations of the two fineness levels led to reductions in β_p values with B45/B10 combination of 25%/75% giving the lowest value. This could be due to the improved overall packing as a result of the wider particle size distribution of the combination (Figure 5-5). The deformation coefficient with this combination was higher than both the other combinations and each type individually and was similar to that of pure PC mix though still showing little significant variation. Henceforth this limestone powder combination was used throughout the project.

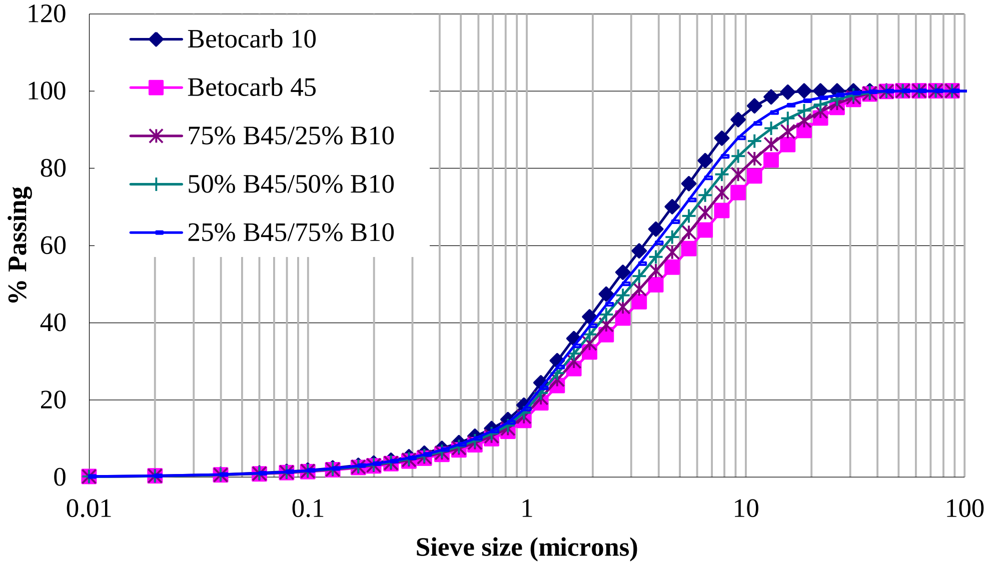


Figure 5-5 Particle size distribution of limestone powder combinations

5.2.7 Heat of hydration

As mentioned in 4.2.1, the heat of hydration tests on the powders were carried out on our behalf by Heriot-Watt University using a JAF Isothermal Conduction Calorimeter. The results for the binary and ternary blended binders are shown in Figure 5-6 and Figure 5-7 respectively; in addition Table 5-6 gives the values of and the time taken to peak heat flow for the different binder compositions.

Table 5-6 Value of and the time taken to peak heat flow for different binder compositions

Mix		Peak heat flow (W/kg of binder)	Time to peak heat (hours)
Reference	100% PC (Control)	3.25	9.6
Binary binder	20% LP	3.03	7.3
	40% GGBS	2.17	9
	80% GGBS	0.99	9.3
	40% FA	2.00	9.5
	80% FA	0.99	12.1
Ternary binder*	TB-40% GGBS	1.97	12.1
	TB-80% GGBS	0.90	8.2
	TB-40% FA	1.80	13.9
	TB-80% FA	0.76	10

*Base powder is a 4/1 ratio of PC and LP (LP is 75%/25% of B10/B45)

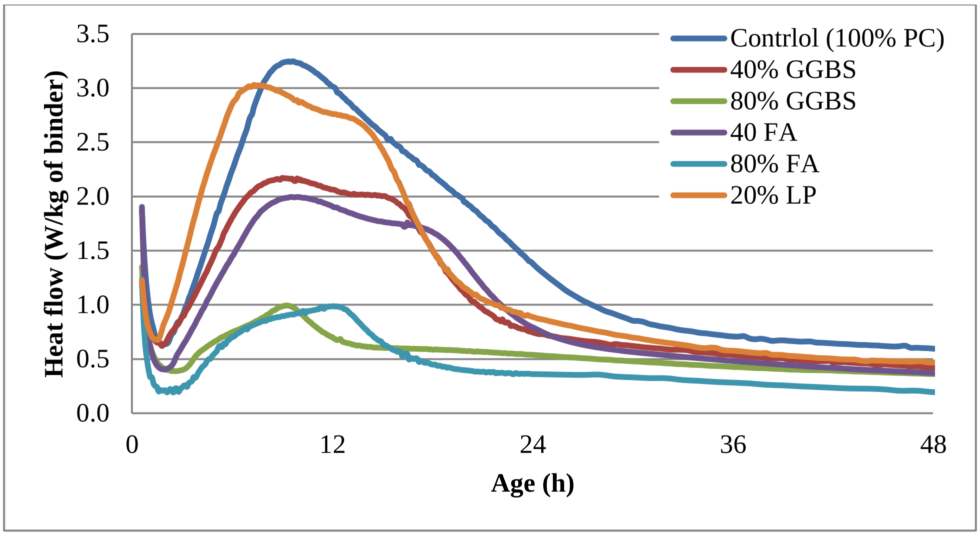
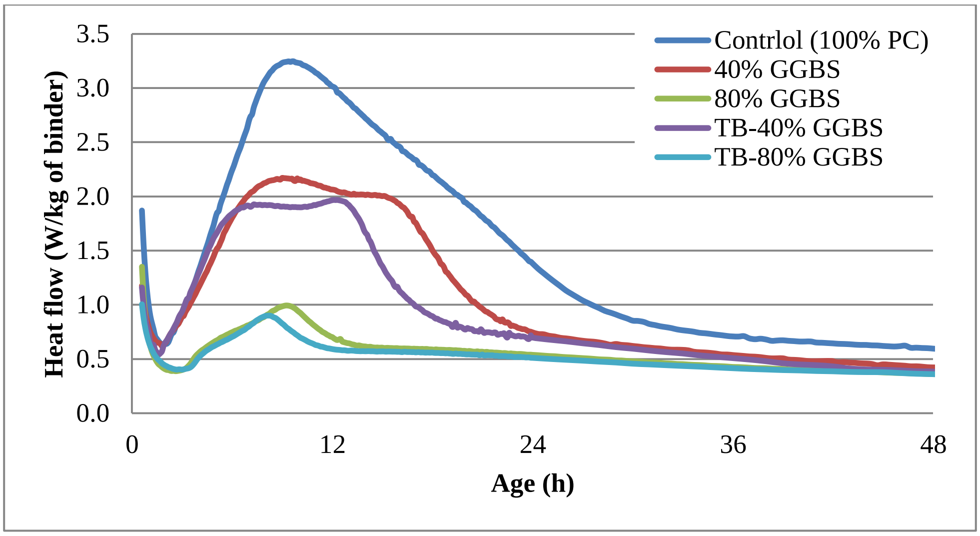


Figure 5-6 Hydration heat output rate for binary binders

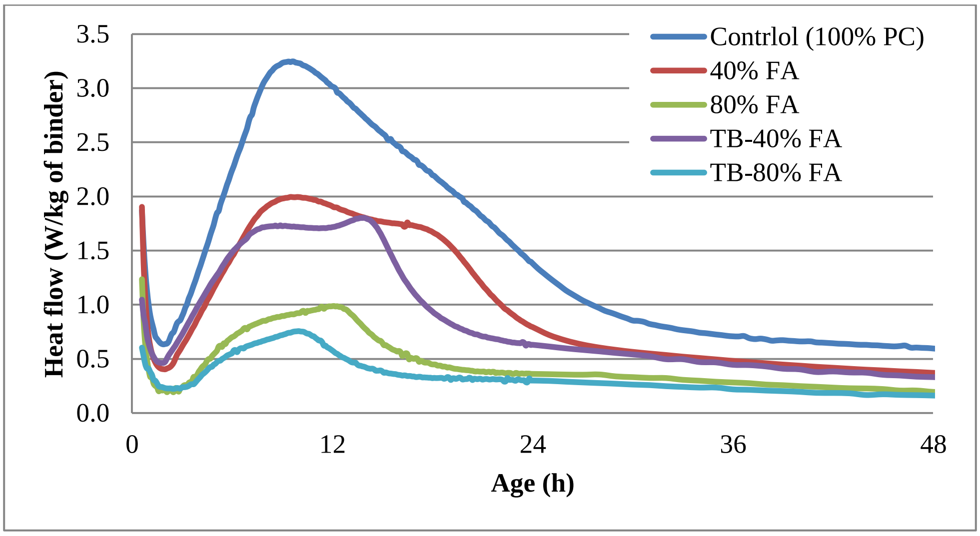
The replacement of Portland cement with the additions resulted in a reduction in the maximum heat flow which is due to both the dilution effect and also the fact that the pozzolanic reaction releases less heat than the Portland cement hydration reaction (Figure 5-6). For example for the binary binder mixes, the maximum heat flow reduced by 7, 34 and 39% with 20% limestone powder, 40% GGBS and 40% FA replacement respectively (Table 5-6). Also the heat flow patterns for the binary binder mixes with limestone powder and those with 40% GGBS and FA show two distinct peaks compared to a single distinct peak of the control mix; the first peak which has a larger magnitude is due to Portland cement hydration whereas the second peak could be due to the catalyst effect of limestone powder increasing the rate of Portland cement hydration. Mixes with 80% GGBS and FA also showed two peaks but here the first peak had a lower magnitude compared to the second as there was less Portland cement available to hydrate initially.

The time taken to reach peak heat flow is also affected by the additions indicating that they do have an influence on the rate of Portland cement hydration. For instance the addition of 40 and 80% FA resulted in delays of 3 and 26% whereas the addition of 20% limestone powder reduced the time taken by about 24% (Table 5-6 and Figure 5-6). The influence of GGBS in this respect was rather low relative to FA and LP. Amongst the additions, the limestone powder mix had the shortest time taken to reach peak heat flow which is again indicative of the catalyst effect of limestone powder. These finding are in agreement with literature (Schindler &

Folliard, 2005; Ballim & Graham, 2009; Mounanga et al., 2011; Wang & Lee, 2012).



(a)



(b)

Figure 5-7 Hydration heat output rate for ternary binders

For the ternary binder mixes, with both GGBS and FA, the maximum heat flow was lower however the time taken to reach the two peaks is shorter compared to their respective binary binder mixes. For ternary binder mixes with 40% replacement, the magnitude of the first peak was lower than the second peak contrary to what was observed with their respective binary binder mixes. The reduction in time taken to reach peaks and the higher magnitude of the second peak could both be due to the presence of limestone powder accelerating the hydration of Portland cement and consequently the secondary reactions with GGBS and FA. Similar trends were observed by Sato & Beaudoin (2011), De Weerdt et al. (2011) and Bentz et al. (2012).

5.3 Water

Ordinary tap water was used as the mixing water throughout the project.

5.4 Admixtures

In this project, three different admixtures were used, a superplasticiser (SP) (for fluidity), a viscosity-modifying agent (VMA) (for stability) and an anti-washout admixture (AWA) (only used in UWC). All the admixtures were commercially available in the UK and ordered from one supplier, Sika (UK), to ensure compatibility. The description and properties of the admixtures is given in Table 5-7 with data sheets given in Appendix 4.

Table 5-7 Description and properties of admixtures

Name	**Type**	**Chemical composition**	**Relative density**	**Solids content (% by weight)**
Sika ViscoCrete 10	High-range water reducer/superplasticiser	Modified polycarboxylate	1.06	30
Sika Stabiliser 4	Viscosity modifying agent	Carbohydrate complex	1.03	15
Sika UCS Powder	Anti-washout admixture	Powder blend of plasticisers and viscosity modifiers	0.33	100

Sika ViscoCrete 10 was used, with all three concrete types, to help achieve the required fluidity in the mix. Due to the high fluidity of SCC, it can be prone to segregation and bleeding, hence Sika Stabiliser 4, a viscosity-modifying agent, was used to reduce these effects. The Sika UCS Powder was only used in underwater concrete mixes to increase the washout resistance of the mix which is a key feature of this type of concrete.

Chapter 6 Mix Designs

In this chapter the mix design methods used to develop the reference control mixes for SCC, FC and UWC are described. Currently there are no British or American standards available for designing concrete mixes; over the years many different methods have been proposed and developed, some more widely used than others. The test methods and constituent materials that are used have been described in Chapter 4 and Chapter 5 respectively.

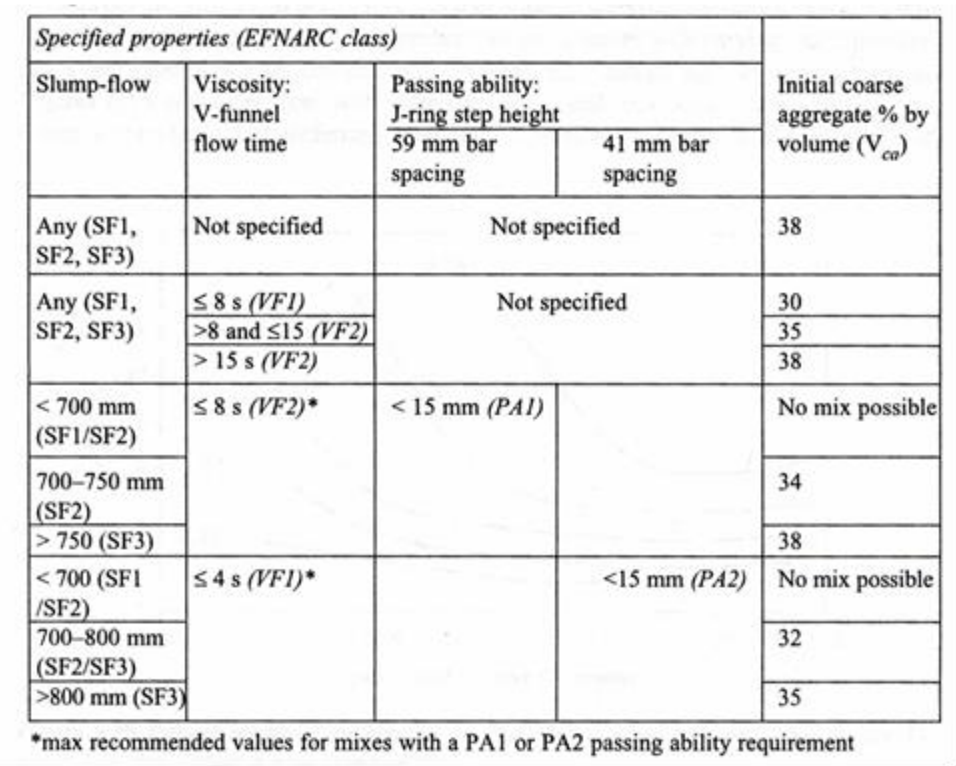
6.1 Self-compacting concrete

One of the main differences between the design of normal-consistence concrete and SCC is that for the former a specific water/cement ratio is chosen initially to meet the concrete strength requirements and the mix design follows on from this to obtaining the proportions of binder and aggregates whereas for SCC, it is its fresh property requirements which govern the mix proportions and not a strength criteria. The strength of SCC can be controlled by using additions to replace part of the Portland cement in the mix. Among these, the general-purpose method is a simple step-by-step method developed from the early extensive work on SCC at the University of Tokyo by Okamura and Ozawa (Okamura & Ozawa, 1995) and the CBI method and its extensions proposed by the Swedish Cement and Concrete Research Institute and developed by Billberg and Petersson (De Schutter et al., 2008).

These two methods have helped create a better understanding of SCC and its wider applications. Based on the experience and understanding gained from the other mix design methods, research on SCC began in 1994 at University College London (UCL) using readily available locally sourced materials and led to the development of a new mix design method for SCC (Domone, 2009). This method was used to obtain the SCC reference control mix due to its simplicity, effectiveness and also its applicability to materials available in the UK. It is mainly based on the correlation between the mortar and concrete properties i.e. spread and V-funnel values. The mix design procedure followed is described below.

1. All the key properties of SCC are influenced by the coarse aggregate content; the initial coarse aggregate content will depend on the specified concrete properties i.e. the target properties in our case (Table 3-1). This method is only applicable for crushed or uncrushed coarse aggregate of 20 or 16mm maximum size; the coarse/fine aggregate division is 4 or 5mm. The coarse aggregate content (V_{ca}) is estimated from Table 6-1. In this project, a coarse aggregate content of 35% was chosen and kept constant throughout the testing programme.

Table 6-1 Initial coarse aggregate content recommended in UCL method
(Domone, 2009)



Specified properties (EFNARC class)				
Slump-flow	Viscosity: V-funnel flow time	Passing ability: J-ring step height 59 mm bar spacing	 41 mm bar spacing	Initial coarse aggregate % by volume (V_{ca})
Any (SF1, SF2, SF3)	Not specified	Not specified		38
Any (SF1, SF2, SF3)	≤ 8 s *(VF1)*	Not specified		30
	>8 and ≤15 *(VF2)*			35
	> 15 s *(VF2)*			38
< 700 mm (SF1/SF2)	≤ 8 s *(VF2)**	< 15 mm *(PA1)*		No mix possible
700–750 mm (SF2)				34
> 750 (SF3)				38
< 700 (SF1 /SF2)	≤ 4 s *(VF1)**		<15 mm *(PA2)*	No mix possible
700–800 mm (SF2/SF3)				32
>800 mm (SF3)				35

*max recommended values for mixes with a PA1 or PA2 passing ability requirement

2. The volume of fine aggregate (V_{fa}) to the resulting mortar volume is set at 45%. It is said that any fine aggregate particles smaller than 125µm, if they constitute greater than 2% of the total mass, should be considered as part of the powder fraction and should not be included in this volume (De Schutter et al., 2008). The fine aggregate used in this project had 3% of its total mass passing that sieve

size (Figure 5-1), hence excluding this portion, the volume of fine aggregate calculated was around 30% of the total concrete volume.

3. At this stage the volumes of Portland cement and water had to be calculated. The water/powder ratio was assumed to be 0.32 by weight (1.0 by volume) where the powder content consisted of both Portland cement and the powder portion of the fine aggregate. Using the remaining volume, the paste volume (35%), and the water/powder ratio, the corresponding volumes of Portland cement and water was calculated to be 16.5 and 17.4% respectively.

4. The optimum water/powder ratio and admixture dosage for achieving the target properties was then obtained from mortar tests, which are simpler and quicker to perform than tests on concrete. Using the given correlations between the mortar and concrete properties and the target properties, the corresponding target mortar properties was obtained. The target slump flow of 700mm and a V-funnel time of about 8s of SCC corresponds to mortar spread of about 325mm (Figure 6-1) and a mortar V-funnel time of about 3s (Figure 6-2). Mortar mixes were then prepared and tested and the water/powder ratio and admixture dosage adjusted, if necessary, to achieve the target mortar properties. Typical effects of varying the water/powder ratio and superplasticiser (SP) dosage on the mortar spread and V-funnel flow time is shown in Figure 6-3.

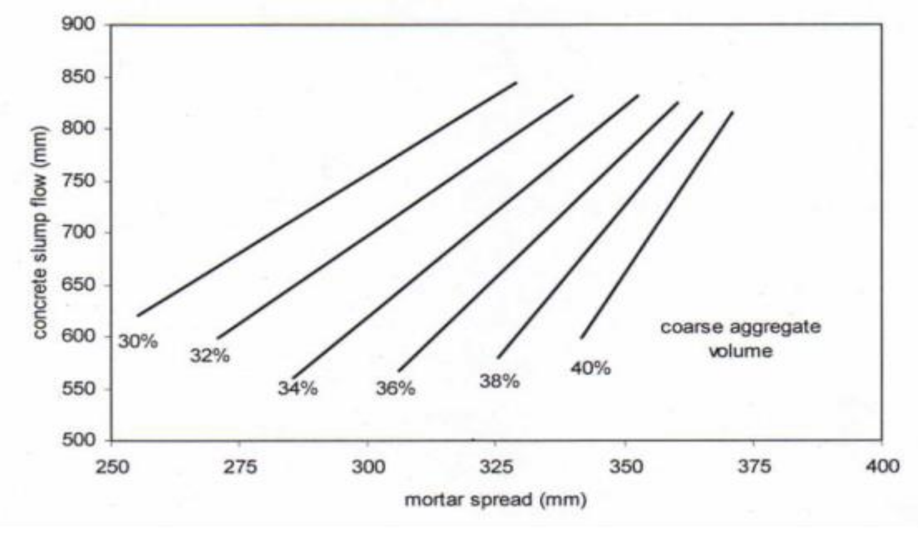


Figure 6-1 Mortar spread vs. slump flow of SCC for various coarse aggregate content (Domone, 2009)

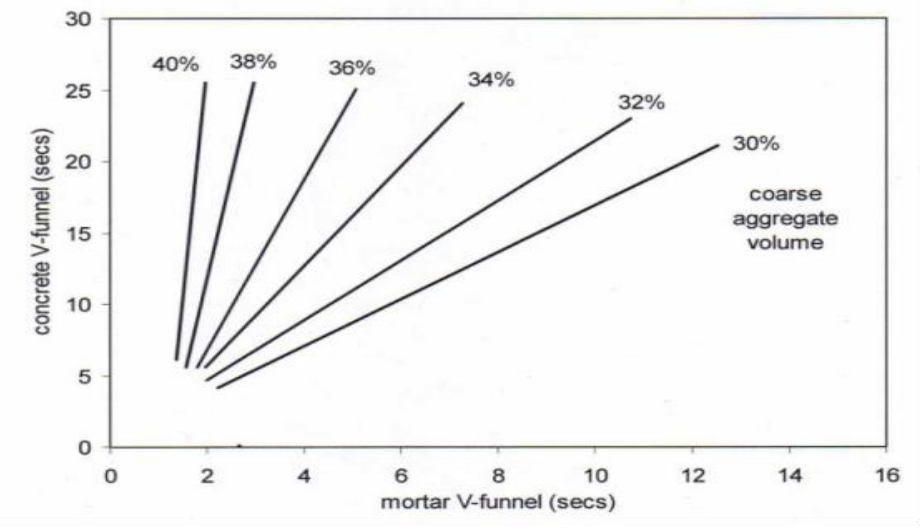


Figure 6-2 V-funnel time of mortar vs. SCC for various coarse aggregate content (Domone, 2009)

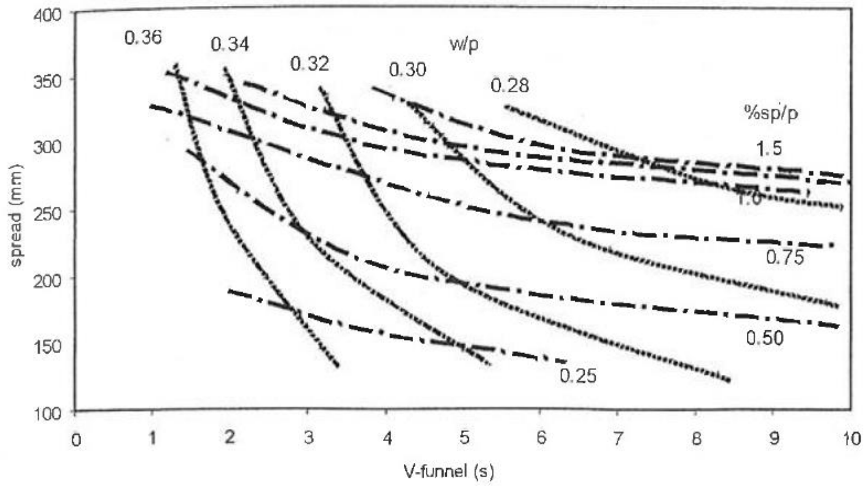


Figure 6-3 Mortar spread vs. V-funnel time showing effects of varying water/powder ratio and superplasticiser dosage (Domone, 2009)

When the mortar target properties were achieved, that water/powder ratio and superplasticiser dosage was then used to produce an SCC mix for which the slump flow and V-funnel time were measured and adjustments made if necessary. Having followed this procedure, the concrete mix meeting all target properties (reference control mix) is shown in Table 6-2. Mortar tests were also used to obtain the optimum water/powder ratio and superplasticiser dosage for all the binary and ternary blended binder mixes prior to production of concrete (Chapter 7).

Table 6-2 SCC reference control mix

Constituent materials	Mix proportions	
	By weight (kg/m^3)	**By volume (%)**
Coarse aggregate 10/20mm	602	23
Coarse aggregate 4/10mm	301	12
Fine aggregate 0/4mm	784	30
CEM I Cement (52.5)	520	16.5
Water	174	17.4
water/powder ratio	0.32	1.0
Sika ViscoCrete 10 (% sp/powder)	1.5	-
	Mix Properties	**Target Properties**
Slump flow (mm)	665	700±50
V-funnel time (s)	6.62	8±3

6.1.1 Influence of admixtures on mortar properties

The few mortar mixes tested to achieve the reference control mix gave minimal information about the performance of the admixtures. It was therefore beneficial to extend the tests on mortar to better understand their effects; this would reduce the number of trial mixes needed to obtain the target properties for the concretes with binary and ternary blend binders. To evaluate the performance of the superplasticiser and the viscosity-modifying agent mortar mixes with varying dosage levels of these admixtures were tested. Six sets of mortar mixes were produced, one with solely Portland cement and the other five incorporating each of the available additions i.e. ggbs, fly ash and 3 different fineness of limestone powder, at their maximum respective replacement levels (Chapter 3). The water/powder ratio was kept constant at 1.0 (by volume) and the effect of admixture dosage on the spread, V-funnel time and the rheological properties of the mortar mixes were measured. The anti-washout admixture was later assessed by tests on concrete, as described in 6.3.

The influence of Sika ViscoCrete 10 on the spread and V-funnel time of the mortar mixes is shown in Figure 6-4 and Figure 6-5 respectively. The increase in superplasticiser dosage resulted in an increase in the spread value and a reduction in the V-funnel flow time as expected. The rate of increase of spread for the same superplasticiser dosage range reduces with the additions; for example an increase in superplasticiser dosage from 1.1 to 1.5% resulted in an increase in the spread value of only about 20mm for the ggbs mix compared to a 4 times higher increase for the control mix of about 80mm (Figure 6-4). This could be because the mixes with additions have a lower saturation dosage (beyond which there is no significant increase in fluidity) (about 1.1%) compared to Portland cement mix (>1.5%) hence the superplasticiser influence on the spread at the same dosage is reduced for mixes with additions. As with the spread, with the V-funnel time, for the same superplasticiser range the rate of decrease in flow time is less with additions; for instance for mixes with additions, the increase in dosage from 1.1 to 1.5% had minimal effect on the flow time compared to the control mix (Figure 6-5) and similarly the binary binder mixes have a lower saturation dosage (~0.9%) compared to the control mix (~1.3%). Superplasticisers have a greater effect on the spread than the V-funnel time. For a given admixture dosage, the spread values are higher for mixes with additions compared to the control mix with the exception of the fly ash mix at dosage of 1.5%, however this gap reduces significantly as the admixture dosage is increased from 1.1 to 1.5% (from 100 to 20mm respectively). Unlike the spread, the V-funnel values for mixes with additions are consistently lower (by about 3-4 seconds) than those for the control mix.

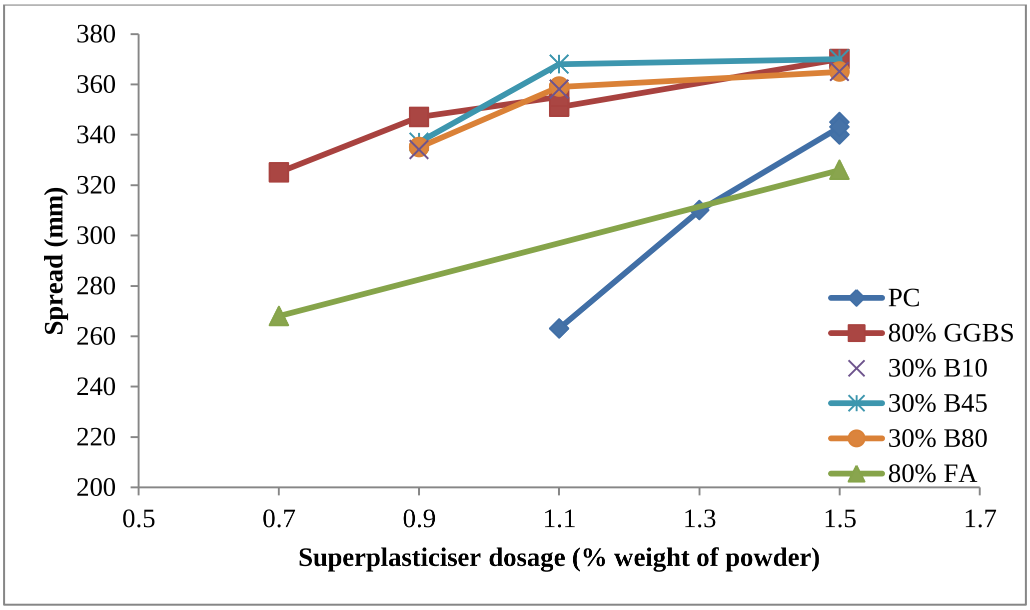


Figure 6-4 Effect of superplasticiser dosage on mortar spread

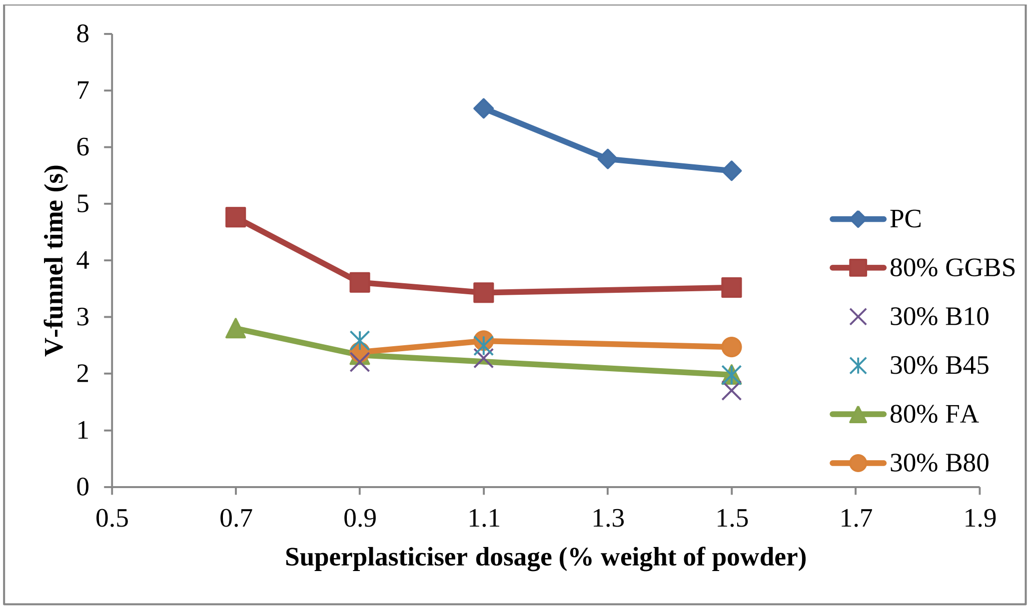


Figure 6-5 Effect of superplasticiser dosage on mortar V-funnel time

Due to the close relationships between yield stress with spread and V-funnel time with plastic viscosity (2.2.3.1), it can be anticipated that the increase in superplasticiser dosage will lead to a decrease in both yield stress (reducing to near zero) and plastic viscosity of the mix. The relationship between the plastic viscosity and the V-funnel time (for all mortar mixes) is shown in Figure 6-6. As anticipated the plastic viscosity increases with an increase in V-funnel time. Due to the high mortar spread, very low (near-zero) values for yield stress were obtained; these were often negative, which have no physical meaning. Hence it was not possible to obtain a relationship between mortar spread and yield stress. It has been reported that the extrapolation or calculation method could result in such negative values for yield stress (Ferraris, 1999). It has also been reported that SCC does not exactly follow the Bingham model (linear) and could be better described by the Herschel-Bulkey model (De Larrard et al., 1998). However this is a non-linear model with three constants making it more difficult to compare these and to relate them to the performance of the mortar. Hence, in this project, linear extrapolation was used (fitting the Bingham model) with negative yield stress values considered as zero.

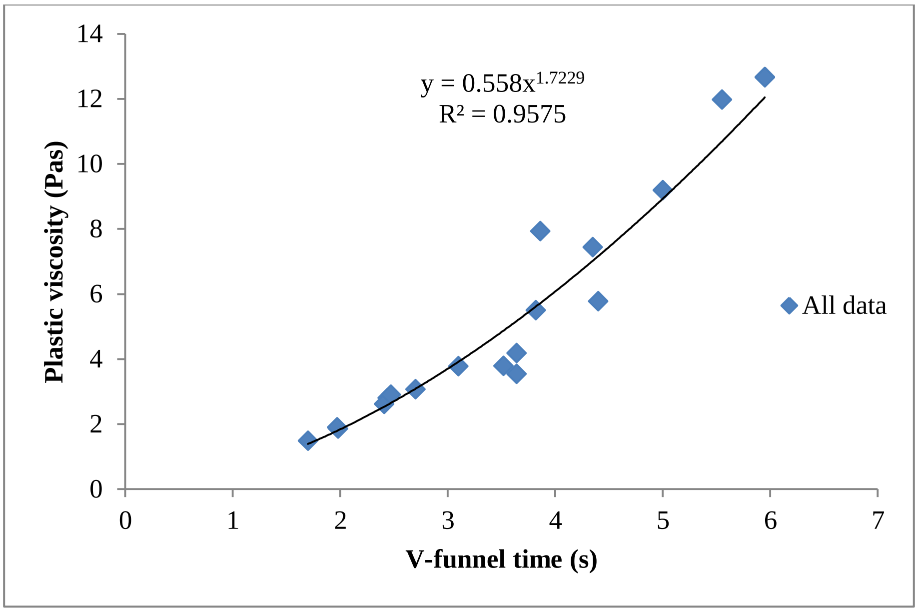


Figure 6-6 Relationship between mortar V-funnel time and plastic viscosity

By reducing the superplasticiser dosage in the mixes with additions it was possible to decrease the spread value to fall within the acceptable range set (320 – 340mm), however, for mortar mixes incorporating fly ash and ggbs at 80% replacement level, it was noticed that the mix with the target spread had excess bleeding (haloes of 10 and 15mm respectively). It was therefore necessary to use a VMA to eliminate this; the dosage in the ggbs mortar mix was increased uniformly and the resulting mix properties measured. The results are shown in Table 6-3 and plotted in Figure 6-7 and Figure 6-8.

Table 6-3 Influence of viscosity-modifying agent on mortar mix

GGBS level (% by volume)	**80**	**80**	**80**	**80**	**80**
VMA (% by weight of binder)	0	0.1	0.2	0.3	0.4
SP(% by weight of binder)	1.5	1.5	1.5	1.5	1.5
Spread (mm)	370	350	350	335	324
V-funnel (s)	3.52	2.79	3.08	3.94	3.96
Yield Stress (Pa)	0	0	0	0	0
Plastic Viscosity (Pas)	3.79	2.26	3.22	5.19	5.65
Halo (mm)	35	20	5	0	0

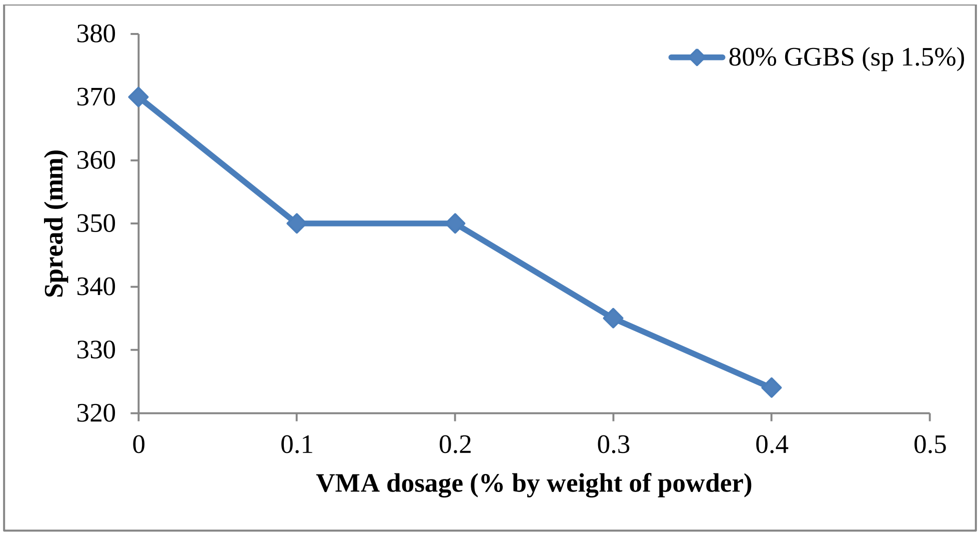


Figure 6-7 Effect of viscosity-modifying agent dosage on mortar spread

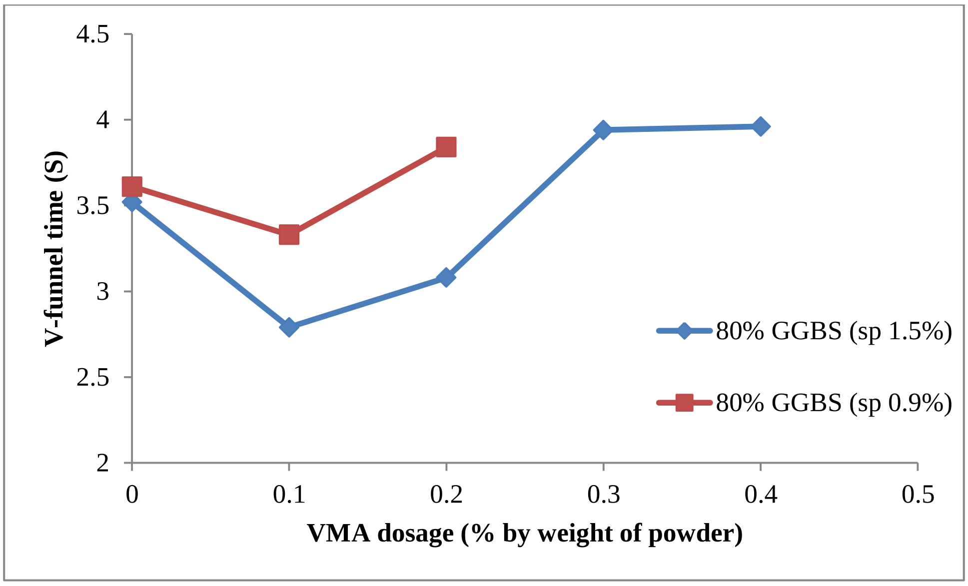


Figure 6-8 Effect of viscosity-modifying agent dosage on mortar V-funnel time

The incorporation of VMA led to a reduction in the spread value and an increase in the V-funnel time (with the exception of 0.1%) which was anticipated as the use of a viscosity-modifying agent increases the viscosity of the mix. In addition to the effects on the spread and V-funnel time, the table shows that, as required, the incorporation of the VMA also led to a reduction in the halo thickness (less bleeding) reducing the risk of segregation from occurring ('stabilising' the mix).

6.2 Flowing concrete

The mix design for FC is relatively simple compared to that of SCC. Neville (2011) described two approaches to designing a mix, one method, probably the simplest, is to design a normal-consistence concrete mix having a slump of 75mm and achieve the higher slump (target slump) by the addition of a superplasticiser. In addition, it is mentioned that for achieving better cohesion, the percentage of fine aggregates is increased by 5% with the coarse aggregate content adjusted accordingly. The second method is to select the fine aggregates in such a way that the total mass of particles smaller than 300µm in the aggregate together with the mass of cementitious materials exceeds 450 kg/m^3 when the maximum size of coarse aggregate is 20mm.

In this project, the FC control mix was designed following the first approach. The BRE mix design (1997) was first used to design a normal-consistence mix after which subsequent adjustments i.e. fine aggregate content and superplasticiser dosage, were made to obtain the reference control mix. The BRE method is governed by strength criteria and for the purpose of this research a target strength of ~55 MPa at 28 days was chosen. The required water/cement ratio was then found to be 0.44 (by weight). Following the mix design steps, the amount of free water, cement content and proportions of aggregates were obtained. The percentage of fine aggregate to total aggregate proportion was then increased by 5% and superplasticiser dosage varied until the slump of a trial mix was within the target range 200 – 240mm (Table 3-1). The consequent reference control mix is given in Table 6-4.

Table 6-4 FC reference control mix

Constituent materials	Mix proportions	
	By weight (kg/m^3)	**By volume (%)**
Coarse aggregate 10/20mm	734	28.4
Coarse aggregate 4/10mm	367	14.2
Fine aggregate 0/4mm	661	25.4
CEM I Cement (52.5)	443	14.1
Water	195	19.5
water/powder ratio	0.44	1.39
Sika ViscoCrete 10 (% sp/powder)	0.5	-
	Mix Properties	**Target Properties**
Slump (mm)	240	220±20

6.3 Underwater concrete

For UWC, the approach taken was to start with typical mix proportions and recommendations from literature. It was found that the typical coarse aggregate content of UWC ranged from 30 – 40% (by volume) and the fine aggregate (sand) to total aggregate ratio was around 45 – 50% (by weight) (Sonebi, 2001; Yao & Gerwick, 2004). Sonebi (2007) and Otuski et al. (1996) both mentioned that lower coarse aggregate content resulted in higher slump flow; the target slump (Table 3-1) can be obtained with a reduced superplasticiser dosage, hence a coarse aggregate content and a fine aggregate to total aggregate content of 32 and 50% respectively were chosen. For structural purposes, it is recommended that UWC should have a washout of about 6 – 8% when tested according to the CRD C61 method (4.3.4.1) (McLennan, 1999; Yao & Gerwick, 2004). However in this project, the target washout was set to 15% or less (Table 3-1), almost twice the recommended value, which was due to the modifications of the test apparatus as discussed in 4.3.4.1. As with FC, a medium strength of ~55MPa at 28 days was chosen, requiring a water/cement ratio of 0.44 (by weight). The coarse and fine aggregate content, water content and the cement content were then calculated.

To obtain the admixture dosage required for the target properties, the performance of the Anti-Washout Admixture (AWA) i.e. Sika UCS Powder, had to be evaluated. Concrete mixes were prepared with varying AWA dosage, keeping the superplasticiser dosage constant, and the amount of washout was measured. The results are illustrated in Figure 6-9. The AWA was very effective in reducing the washout, with a dosage of 0.5% (at an SP dosage of 0.5%), the washout reduced from near 50% to less than 10%. The addition of the AWA also resulted in a decrease in the slump value (250 to 210mm) and increase in both yield stress and plastic viscosity. The slump value seemed to stay constant as the AWA dosage was increased from 0.25 to 0.75%, however the value of the yield stress carried on increasing which could have been due to the increased 'stickiness' of the mix with increasing dosage. The SP dosage was increased to 1.2% to achieve the required initial slump, however as expected this resulted in higher washout.

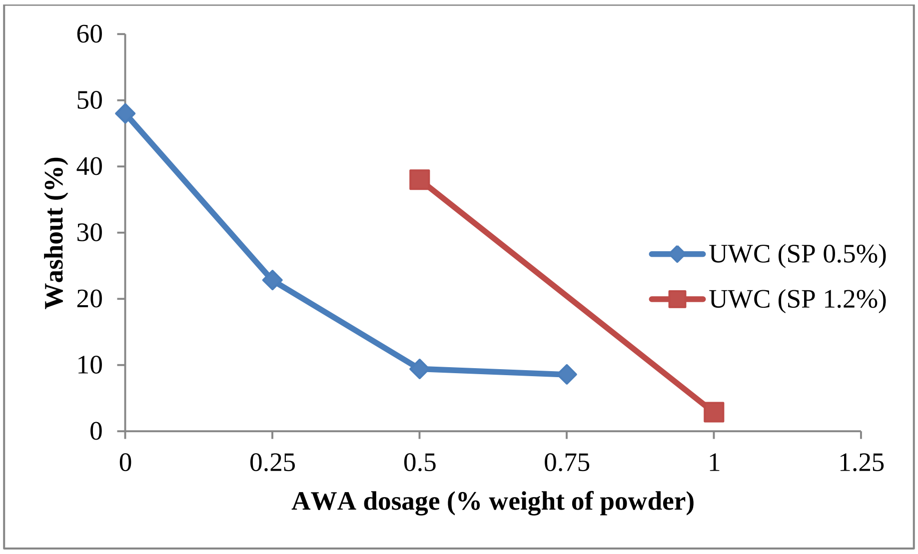


Figure 6-9 Effect of AWA dosage on washout resistance of UWC

The effect of AWA dosage on the slump was also evaluated. A set of mortar mixes were prepared with different AWA dosage, all having a spread of about 180±20mm. The SP dosage was varied to obtain the required spread value. The results are shown in Figure 6-10. As expected, the SP dosage required for maintaining constant mortar spread increased with the increase of AWA dosage. Having understood the influence of AWA dosage on both washout and slump value, it was then possible to find the required SP and AWA dosage to achieve the concrete's target properties with a minimal number of trials. The resulting reference control mix is given in Table 6-5.

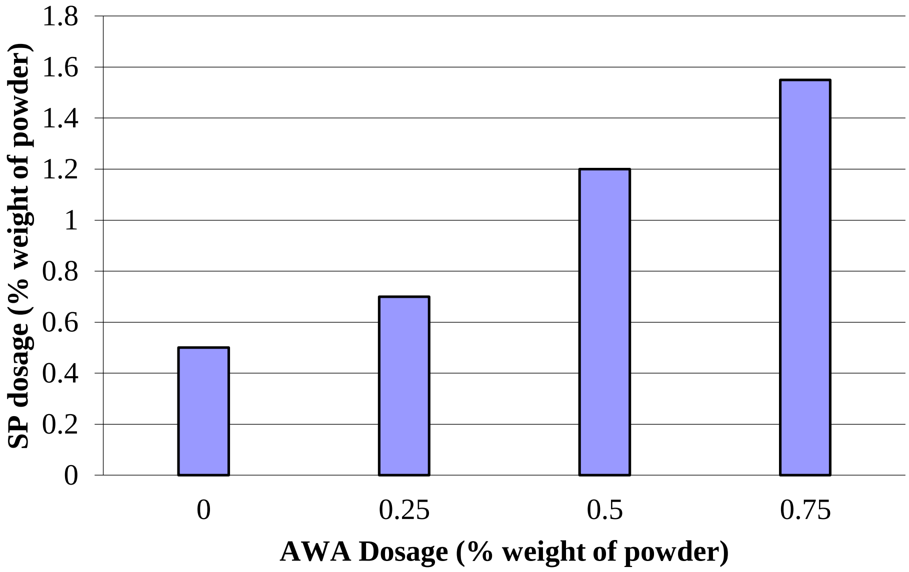


Figure 6-10 SP dosage for constant mortar spread with varying AWA dosage

Table 6-5 UWC reference control mix

Constituent materials	**Mix proportions**	
	By weight (kg/m^3)	**By volume (%)**
Coarse aggregate 10/20mm	551	28.4
Coarse aggregate 4/10mm	275	14.2
Fine aggregate 0/4mm	848	25.4
CEM I Cement (52.5)	475	14.1
Water	209	19.5
water/powder ratio	0.44	1.39
Sika ViscoCrete 10 (% sp/powder)	0.7	-
Sika UCS Powder (% AWA/powder)	0.5	-
	Mix Properties	**Target Properties**
Slump (mm)	215	220±20
Washout (%)	9	≤15

6.4 Conclusions

This chapter described the mix design methods used to obtain the reference control mixes for SCC, FC and UWC. In addition, the influence of admixtures on mortar properties were assessed and discussed. The main conclusions drawn from this chapter are given below:

Mix designs

1. Unlike normal-consistence concrete where strength is a key requirement governing the water/cement ratio and hence the mix proportions, for SCC, it is the fresh properties which govern the mix proportions and strength is secondary to this. Among the various methods available in the literature such as the general-purpose method by Okamura and Ozawa and the CBI method and its extensions proposed by the Swedish Cement and Concrete Research Institute, it was decided to adapt a more recent method, based on the correlation between the mortar and concrete properties developed at University College London from extensive research of SCC using locally sourced materials due to its simplicity, effectiveness and its applicability to materials available in the UK.

2. Two mix design methods were suggested for FC; the first is where you initially design a normal concrete mix having a slump of 75mm and achieve the higher slump with the incorporation of a superplasticiser and the second method is where you select the fine aggregate in such a way that the total mass of particles smaller than 300μm together with the mass of the cementitious materials exceeds 450 kg/m^3. In this project the former approach was used to obtain the mix proportions for the FC reference control mix. The mix was designed to have a medium strength level i.e. ~55MPa.

3. Unlike SCC and FC, no suggested method was available within the literature hence the suggested coarse aggregate content and fine aggregate to total aggregate ratios were used to obtain a mix design. The values used were 32 and 50% respectively. As with FC, this mix was also designed to have a medium strength level. The reference control mixes for all three concrete types were developed accordingly.

Admixture influence on mortar properties

4. In mortar mixes, the increase in superplasticiser dosage resulted in an increase in the spread and a reduction in V-funnel flow time. Unlike the superplasticiser, the incorporation of a VMA led to a reduction in the mortar spread and an increase in the V-funnel time. The use of AWA had a positive effect of reducing the washout however at the same time led to a reduction in spread hence an increase in superplasticiser dosage is required to compensate for the loss in spread; for a mix with 0.5% AWA, the superplasticiser dosage had to increase from 0.5% (for the control mix) to just over 1% to achieve the same spread value.

5. For the same superplasticiser dosage, the incorporation of addition resulted in an increase in spread and a reduction in V-funnel flow time compared to the pure PC mix. The rate of increase of spread for the same superplasticiser range was lower for mixes with additions as those mixes have a lower saturation dosage i.e. dosage beyond which there is no significant increase in fluidity. For the same superplasticiser dosage, the V-funnel flow time for mixes with additions was consistently lower (by 3-4 seconds) than those for the pure PC mix.

6. There is a close relationship between the mortar V-funnel flow time and plastic viscosity of the mixes; as the V-funnel flow time increases so does the plastic viscosity of the mix.

Chapter 7 Self-Compacting Concrete Results

In this chapter, the result of tests on SCC with different binder compositions, both binary and ternary blends (Table 3-1), are presented and discussed. Tests were initially carried out on mortar mixes to assess the effects of the different additions i.e. ggbs, fly ash and limestone powder, at various replacement levels, on the fresh properties. The admixture dosages were then adjusted to obtain the target values of spread and V-funnel time i.e. 325±20mm and 3±2s respectively, at each different binder composition. These dosage levels were then used to produce the corresponding SCC mixes and further adjusted, if necessary, until the concrete target properties were achieved i.e. slump flow 700±50mm, V-funnel time 8±3s, J-ring step height ≤15mm and sieve segregation of less than 15%. The hardened properties of the mixes were then measured, as described in 4.4, at ages 1, 3, 7, 28, 56 and 91 days.

7.1 Effect of additions on mortar properties

Since the densities of the additions are lower than that of Portland cement, replacements by weight would lead to higher powder content (increase in powder volume) and subsequent reduction in the volume fraction of water and fine aggregate in the mortar which would influence its fresh properties (Bentz et al., 2011). Hence to study the influence of solely the additions on the mortar properties, replacements were made by volume keeping the water/powder ratio by volume constant at 1.0. The dosage of the superplasticiser was expressed as percentage of total powder weight and also kept constant at 1.5% as in the control mortar mix (Table 6-2).

The replacement of Portland cement with ggbs led to an increase in spread and a reduction in the V-funnel time (Figure 7-1) as ggbs replacement increases. There was a significant increase in the spread value when the replacement level was increased from 20 to 40% (345 to 370mm respectively); with no change thereafter as the replacement levels were increased to 60 and 80%.

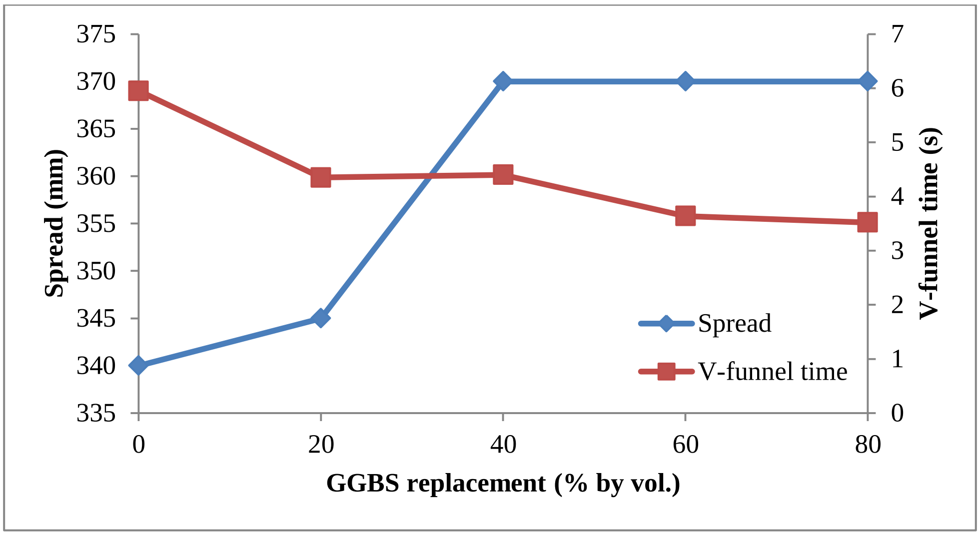


Figure 7-1 Effects of ggbs replacement level on fresh mortar properties

Table 7-1 Effects of ggbs on bleeding and rheological properties of mortar

GGBS level (% by volume)	**0**	**20**	**40**	**60**	**80**
SP (% by weight of powder)	1.5	1.5	1.5	1.5	1.5
Yield Stress (Pa)	0	0	0	0	0
Plastic Viscosity (Pas)	12.7	7.44	5.78	3.54	3.79
Halo (mm)	0	10	15	25	35

The addition of ggbs also led to an increased segregation; the halo of bleed water around the outer edges of the mortar after reaching its final spread increased from 0 to 35mm as the ggbs replacement level was increased from 0 to 80% (Table 7-1). Even though the spread value stayed constant for replacement levels 40, 60 and 80%, the halo thickness continued to increase with increasing replacement levels indicating a higher risk of segregation. As shown in Table 5-4, the addition of ggbs decreased the retained water ratio of the paste; hence reducing the paste water demand. This could be the reason for the excess bleed water since the water content was kept constant the particles were unable to contain all the water resulting in the formation of a halo. The V-funnel time reduced from 6 to 2s as the ggbs replacement level was increased from 0 to 80%. The inclusion of ggbs led to a reduction in the plastic viscosity (Table 7-1) i.e. as in Figure 6-6.

As with ggbs, the inclusion of fly ash led to a reduction in the V-funnel time, with a significant drop noticed when the replacement level increased from 20 to 40% (Figure 7-2). This was also reflected in the plastic viscosity results (Table 7-2); the viscosity decreased from 12 to 3.78Pas with the increase in replacement level. This is in agreement with Banfill (2011), Newman and Choo (2003) and Güneyisi & Gesoğlu (2008), however contradicts findings by Xie et al. (2002) and Turk (2012). The reason for these contradictory findings could be due to the variation in type and source of the fly ash used. Also different superplasticisers influence the mix viscosity differently; hence this could also be another reason for the differences in the findings (Chen et al., 2012; Banfill, 2011; Björnström & Chandra, 2003; Masood & Agarwal, 1994). Figure 7-2 also shows that the spread of the mortar increased with increasing fly ash content up to 40% and then, surprisingly, decreased thereafter. There was a relatively larger decrease in spread when the fly ash replacement level was increased from 60 to 80% (346 to 326mm respectively) than from 40 to 60% (350 to 346mm respectively). This may be because the effectiveness of the superplasticiser, being designed for cement-based mixtures, is reduced at these replacement levels resulting in lower deformation capacity.

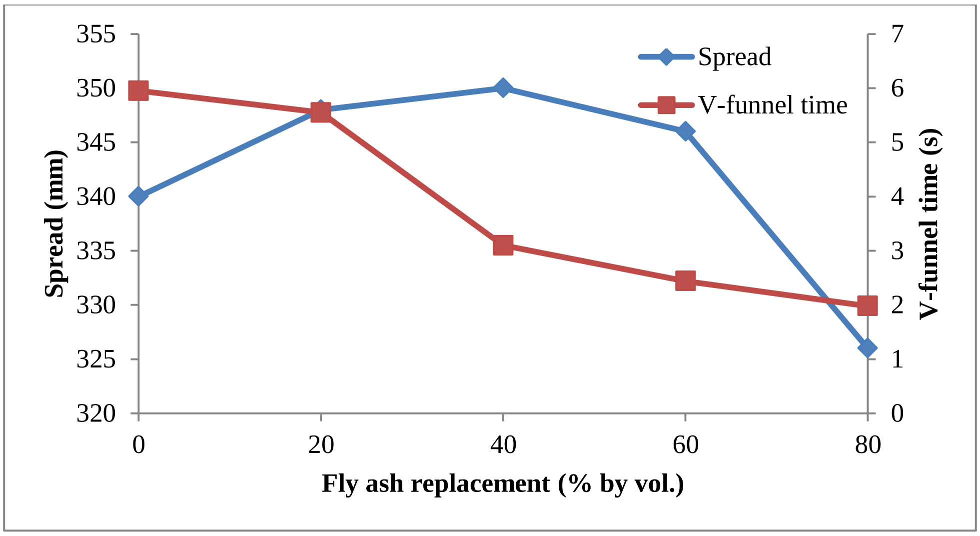


Figure 7-2 Effects of fly ash replacement level on fresh mortar properties

Table 7-2 Effects of fly ash on bleeding and rheological properties of mortar

Fly Ash level (% by volume)	**0**	**20**	**40**	**60**	**80**
SP (% by weight of powder)	1.5	1.5	1.5	1.5	1.5
Yield Stress (Pa)	0	0	0	0	0
Plastic Viscosity (Pas)	12.7	12	3.78	2.8	1.86
Halo (mm)	0	0	10	13	17

The replacement of Portland cement with fly ash also resulted in increased bleeding indicated by the halo thickness around the mortar which increased with increasing fly ash replacement level (Table 7-2). As with ggbs, inclusion of fly ash lowers the retained water ratio (Table 5-4) which could explain the excess bleed water with increasing fly ash content, however, for the same replacement level, the reduction in the retained water ratio with fly ash is greater than that with ggbs but, contrary to what was expected, the bleeding was higher with ggbs than with fly ash, hence the results are inconsistent in this respect.

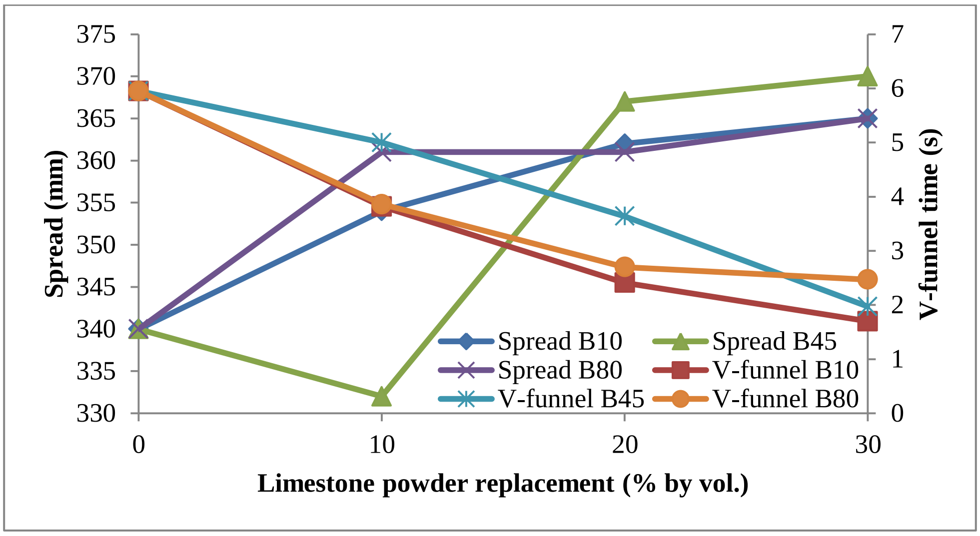


Figure 7-3 Effects of limestone powder replacement level on fresh mortar properties

Limestone powder mixes incorporating each of the different types i.e. Betocarb 10, 45 and 80 (5.2.4) were tested; the results are shown in Figure 7-3. As with both ggbs and fly ash, increase in limestone powder replacement, for all three types, led to higher mortar spread, with the exception of the mix with 10% B45, and lower V-funnel flow time. The effect on the V-funnel time is also mirrored by the plastic viscosity results with increasing limestone powder replacement resulting in lower plastic viscosity (Table 7-3). The effects of B10 and B80 limestone powders seem to be very similar on both the spread and V-funnel time. The effects of B45, on the other hand, the spread at 10% replacement level was 10mm lower than the control and the V-funnel flow time was about one second higher at replacement levels of 10 and 20% compared to mixes with B10 and B80. Also, with increasing replacement levels, the V-funnel time seems to be levelling off for B10 and B80 mixes whereas for B45 mixes it seems to be decreasing further and at a slightly higher rate. Again as with ggbs and fly ash, increase in limestone powder replacement increased the risk of segregation (Table 7-3), with the B10 mixes having the highest risk (halo thickness of 25mm at 30% replacement level) followed by B80 mixes and B45 mixes with halo thicknesses, at 30% replacement level, of 15 and 10mm respectively. The addition of limestone powder also reduced the retained water ratio of the mix which could be the cause of the halo formation (Table 5-4). The mix with 20% B45 gave a lower retained water ratio (1.29) compared to the corresponding B10 mix (1.36), however the halo thickness of the mixes were 5 and 10mm respectively, hence this contradicts the assumption made earlier that a lower retained water ratio would lead to higher bleeding as there would be less water-filled voids.

Table 7-3 Effects of limestone powder on bleeding and rheological properties of mortar

Limestone (B10) level (% by volume)	**0**	**10**	**20**	**30**
SP (% by weight of powder)	1.5	1.5	1.5	1.5
Yield Stress (Pa)	0	0	0	0
Plastic Viscosity (Pas)	12.7	5.5	2.62	1.49
Halo (mm)	0	3	10	25
Limestone (B45) level (% by volume)				
SP (% by weight of powder)	1.5	1.5	1.5	1.5
Yield Stress (Pa)	0	0	0	0
Plastic Viscosity (Pas)	12.7	9.19	4.18	1.9
Halo (mm)	0	0	5	10
Limestone (B80) level (% by volume)				
SP (% by weight of powder)	1.5	1.5	1.5	1.5
Yield Stress (Pa)	0	0	0	0
Plastic Viscosity (Pas)	12.7	7.93	3.07	2.9
Halo (mm)	0	0	10	15

Having tested the effects of these additions and of the chemical admixtures on mortar properties (6.1.1), the admixture dosages were then adjusted to obtain the target mortar properties for both binary and ternary blended binders. The resulting dosages and mortar properties are given in Table 7-4 and Table 7-5. As discussed in 5.2.5 and 5.2.6, a 25%/75% combination of B45/B10 limestone powders was used throughout this project, however its effects on fresh mortar properties was not tested as knowing the effects of the individual powders was sufficient to directly obtain the target mortar mixes.

Table 7-4 Target mortar mixes with binary blended binder mixes

GGBS level (% by volume)	**20**	**40**	**60**	**80**
VMA (% by weight of powder)	0.1	0.1	0.1	0.2
SP (% by weight of powder)	1.3	1.1	0.9	0.9
Spread (mm)	322	324	324	333
V-funnel (s)	5.07	4.3	4.24	3.84

(a)

Fly Ash level (% by volume)	**20**	**40**	**60**	**80**
VMA (% by weight of powder)	0	0	0.1	0.2
SP (% by weight of powder)	1.1	0.9	0.9	0.9
Spread (mm)	332	331	332	331
V-funnel (s)	3.34	2.54	1.66	1.37

(b)

Limestone 75B10/25B45 level (% by volume)	**10**	**20**	**30**
SP (% by weight of powder)	1.3	1	0.9
Spread (mm)	328	333	318
V-funnel (s)	3.68	2.34	2.4

(c)

Table 7-5 Target mortar mixes with ternary blended binder mixes

TB - GGBS level (% by volume)	**20**	**40**	**60**	**80**
VMA (% by weight of powder)	0.2	0.2	0.2	0.2
SP (% by weight of powder)	1.1	1.1	0.9	0.9
Spread (mm)	320	336	323	333
V-funnel (s)	3.15	2.66	3.5	2.89

(a)

TB - Fly Ash level (% by volume)	**20**	**40**	**60**	**80**
VMA (% by weight of powder)	0.1	0.1	0.2	0.3
SP (% by weight of powder)	1	0.9	0.9	0.9
Spread (mm)	328	339	328	324
V-funnel (s)	1.9	1.69	1.53	1.41

(b)

The required superplasticiser dosage for the target binary and ternary binder mortar mixes was lower than the control mix dosage (1.5%) and, for all the three additions, decreased with increasing replacement level. For replacement levels of 60 and 80% replacement, for fly ash and ggbs, the superplasticiser dosage levels were the same at 0.9% (Table 7-4). As mentioned, the main issue with these high replacement levels was excess bleeding; reduction in the dosage did eliminate the bleeding but also reduced the spread to below the target value, hence the VMA was used to eliminate the bleeding and the superplasticiser dosage was kept constant to achieve the required spread.

For the mortar mixes with ternary blended binders (Table 7-5), the superplasticiser dosage levels were the same as that in binary binder mixes, with the exception of the mixes with 20% replacement level where for ggbs and fly ash mixes the dosage was reduced by 0.2 and 0.1% respectively. On the other hand a higher VMA dosage was required by the ternary mixes indicating higher bleeding, hence increased segregation. This is also mirrored by the retained water ratio values of these mixes (Table 7-6) which are lower compared to that of binary binder mixes (Table 5-4). For example, the retained water ratio of binary binder mixes with 20 and 80% ggbs replacement was 1.212 and 1.084 respectively compared to 1.176 and 1.024 for the corresponding ternary binder mixes and similarly for fly mixes the ratio was 1.157 and 0.779 compared to 1.064 and 0.726 respectively.

Table 7-6 Retained water ratio and deformation coefficient of ternary binder combinations

Powder	**β_p**	**E_p**
TB-GGBS		
20% replacement	1.176	0.051
40% replacement	1.144	0.050
60% replacement	1.080	0.048
80% replacement	1.024	0.048
TB-Fly Ash		
20% replacement	1.064	0.057
40% replacement	0.920	0.062
60% replacement	0.884	0.046
80% replacement	0.726	0.050

The fresh properties of the concrete mixes resulting from the mortar mixes are given in Table 7-7 with the full mix proportions given in Appendix 5. For some of these mixes, the SP and VMA dosages had to be adjusted slightly (±0.1%) from that used in the mortar mixes to ensure the target fresh properties were achieved. For most cases, it was only necessary to adjust the dosage of one of the admixtures with the exceptions being ternary binder mixes with fly ash where both dosages needed to be adjusted. For example, for the ternary binder concrete mix with 60% fly ash replacement (SCC-TB-F60), the SP dosage was reduced by 0.1% and the VMA dosage was increased by the same amount.

Table 7-7 Fresh properties of SCC mixes

Mix no.	Mix ref.	Slump flow	J-ring		V-funnel time	Two-point test		Sieve segregation
			Step	Spread		Yield stress	Plastic viscosity	
		(mm)	(mm)	(mm)	(s)	(Pa)	(Pas)	(%)
1	SCC-C	665	15	590	6.62	106	37	13
2	SCC-L10	730	9	690	7.29	0	38	14
3	SCC-L20	670	10	620	6.73	16	20	15
4	SCC-L30	680	10	630	7.25	10	34	12
5	SCC-G20	735	10	650	8.43	113	62	12
6	SCC-G40	730	9	660	8.41	125	64	7
7	SCC-G60	705	13	620	8.58	210	52	6
8	SCC-G80	660	13	530	7.32	300	43	3
9	SCC-F20	660	14	580	8.19	218	39	5
10	SCC-F40	660	12	570	5.82	36	38	12
11	SCC-F60	720	9	660	5.85	0	16	15
12	SCC-F80	680	13	580	3.52	13	12	12
13	SCC-TB-G20	700	13	650	6.48	37	31	13
14	SCC-TB-G40	650	10	570	7.24	34	36	5
15	SCC-TB-G60	660	13	575	7.31	102	43	5
16	SCC-TB-G80	660	13	565	8.43	165	71	4
17	SCC-TB-F20	730	8	675	9.31	47	28	15
18	SCC-TB-F40	680	8	600	4.14	21	18	14
19	SCC-TB-F60	675	12	605	4.21	20	18	15
20	SCC-TB-F80	665	9	590	3.38	15	18	10

Unlike the mortar mixes, it is not possible to isolate the effects of the additions on the fresh properties of SCC from the results in Table 7-7, as the admixture dosage was adjusted for all mixes to achieve the target fresh properties. However an indirect indication can be obtained from the admixture dosages required for each mix. The general trend was still similar to that with the mortar mixes in that for all three additions, increase in replacement level led to reduction in the required SP dosage and increase in VMA dosage. As with the mortar mixes, due to the small range of slump flow, no correlation is expected between that and the yield stress and that is the case whereas a distinct correlation exists between the V-funnel time and the plastic viscosity, but with a small number of outliers (Figure 7-4).

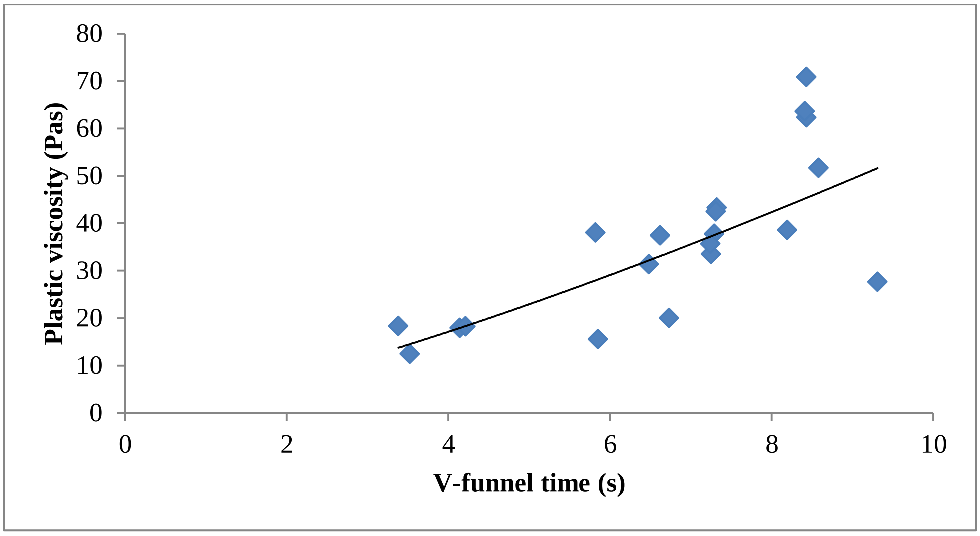


Figure 7-4 Relationship between plastic viscosity and V-funnel flow time for SCC mixes

7.2 Effect of additions on hardened mechanical properties of self-compacting concrete

In this section the results of the two strength tests, i.e. cube compressive and tensile splitting, and the two non-destructive tests, i.e. ultrasonic pulse velocity and dynamic elastic modulus, are given and discussed. All the values are average of three measurements (4.5); the complete data sets are given in Appendix 6.

7.2.1 Compressive strength

7.2.1.1 Binary binder mixes

Considering mixes with ggbs, the early-age strength (up to 7 days) was less than that of the control mix with the difference increasing at higher replacement levels. Referring to Table 7-8 and Figure 7-5 (a), the 1-day strength of mix with 20 % ggbs (SCC-G20) was about 25MPa compared to 33MPa for the control mix, a reduction of 24% whereas the mix with 80% ggbs had a reduction in strength of about 83%. This is expected as the ggbs hydration reaction rate is slow and it is the products of the Portland cement hydration which act as a catalyst for this reaction; hence, at early ages, the greater the amount of ggbs, the less the amount of Portland cement that is available to hydrate and give strength (2.4.1). Mixes with ggbs replacements of up to 40% achieved comparable strengths to that of the control mix at 28 days and above. The mix with 40% ggbs attained similar 91-day strength to that of the control mix (about 70MPa) whereas the mix with 20% ggbs attained a slightly higher strength of about 74MPa. Mixes with 60 and 80% ggbs both attained lower strengths than the control mix. This is in agreement with the literature that ggbs mixes can, in the long-term, due to the secondary hydration reaction, achieve similar or higher strengths compared to pure Portland cement mixes with the optimum replacement level being about 50% (2.4.1.3).

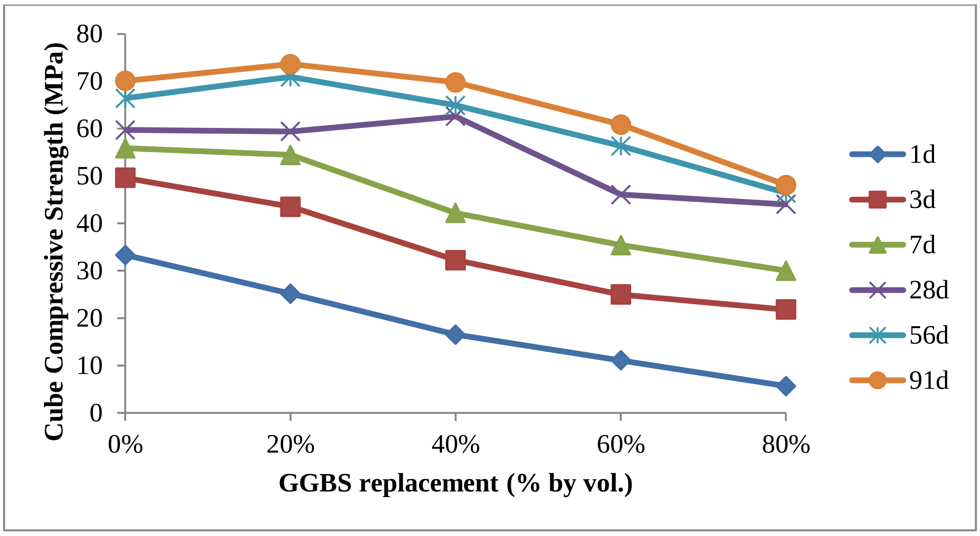
Table 7-8 Cube compressive strength of SCC mixes

			Compressive strength (MPa)					
Binder	**Mix no./Age (days)**		**1**	**3**	**7**	**28**	**56**	**91**
Control (PC)	1	0%	33.3	49.6	55.9	59.7	66.4	70.1
Limestone	2	10%	26.3	43.5	50.3	57.1	59.1	74.2
	3	20%	25.4	36.1	40.8	47.0	53.3	66.2
	4	30%	20.5	29.8	41.2	49.5	57.5	64.4
GGBS	5	20%	25.2	43.5	54.4	59.4	70.9	73.6
	6	40%	16.5	32.3	42.2	62.6	64.9	69.8
	7	60%	11.1	25.0	35.4	46.1	56.4	60.9
	8	80%	5.7	21.8	30.0	44.0	46.4	48.1
Fly Ash	9	20%	28.2	43.5	45.9	56.5	67.9	71.0
	10	40%	16.9	29.9	37.5	50.2	58.7	61.3
	11	60%	4.1	12.2	16.6	28.0	32.8	37.2
	12	80%	1.4	3.6	4.9	7.6	10.9	14.3
Ternary Binder-GGBS	13	20%	14.0	31.1	40.1	54.1	70.8	76.6
	14	40%	7.8	26.0	38.6	54.3	70.2	73.3
	15	60%	5.8	22.2	34.7	49.2	60.3	62.7
	16	80%	3.3	19.0	29.7	42.0	49.5	50.1
Ternary Binder- Fly Ash	17	20%	14.4	33.4	38.5	65.5	68.1	73.5
	18	40%	6.3	18.3	25.0	41.8	48.0	51.2
	19	60%	2.0	8.4	12.2	25.6	31.0	34.6
	20	80%	0.6	2.1	3.1	6.7	9.1	10.2

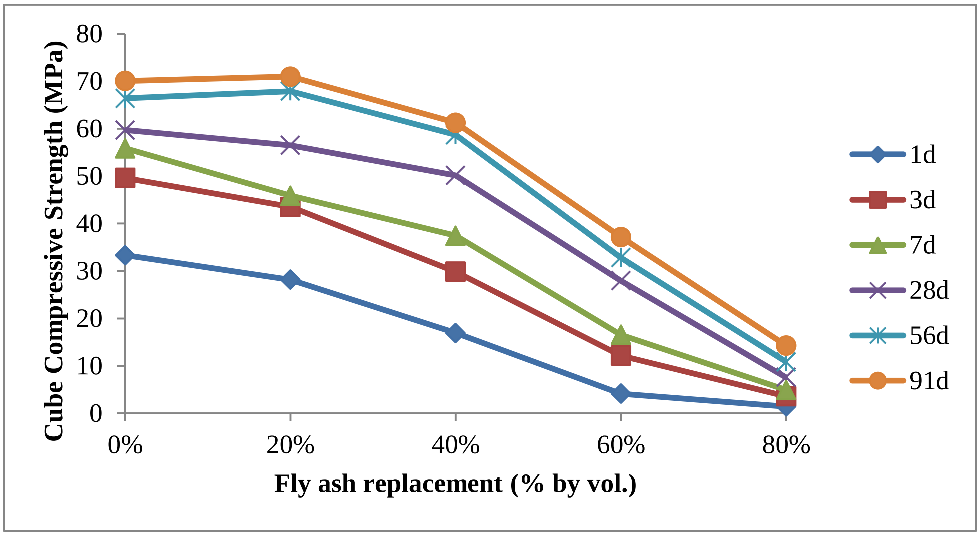
As with ggbs, mixes containing fly ash also had lower early-age strength compared to the control mix with the difference being greater at higher replacement levels (Figure 7-5 (b)). For example the 1-day strength of SCC-F20 (20% fly ash) is about

28MPa compared to 33MPa for the control mix (Table 7-8), a reduction of 15%, however SCC-F80, having 80% fly ash, attained a strength of only 1.4MPa, which is a 95% reduction. A noticeable difference between ggbs and fly ash mixes (Figure 7-1 (a) and (b) respectively) is in that the latter the rate of strength loss is higher at replacement levels over 40%. For instance, the strength loss of the mix with 80% ggbs at 91 days was about 33% whereas the same mix with fly ash had a strength loss of 80%. This can be attributed to the fact that fly ash is a true pozzolanic material hence relies on the formation of $Ca(OH)_2$ from Portland cement hydration to react with and form C-S-H (2.4.2). Hence with fly ash, only mixes containing 20% replacement obtained comparable strength at later ages with higher replacement levels achieving lower strengths, for example the 91-day strength of SCC-F20 mix was 71MPa with the control mix attaining a strength of 70MPa whereas mixes with 40, 60 and 80% fly ash had strengths of 61, 37 and 14MPa respectively. It should however be noted that a contributing factor to these low strength levels is the increasing water powder ratios by weight with fly ash replacement, due to its low relative density. Nevertheless, as with ggbs, fly ash mixes can obtain comparable long-term strengths with Portland cement mixes however the optimum replacement levels is only about 30% as above this level there is insufficient Portland cement to produce the amount of $Ca(OH)_2$ required to react with all the silica in the fly ash.

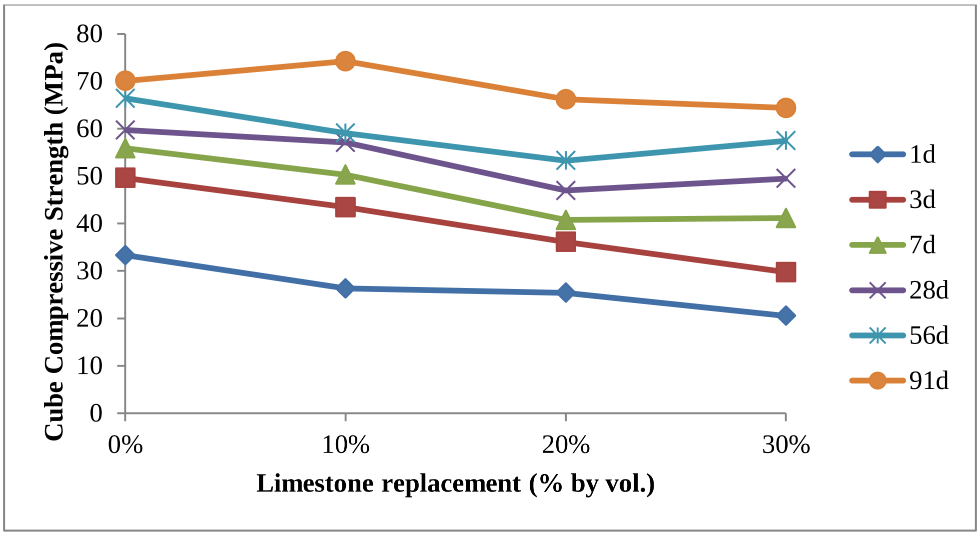
Comparing the mixes with limestone powder, at early ages the decrease in strength was greater with increasing replacement level than at later ages. For example, looking at Figure 7-5 (c), considering the 3-day strength, the control mix (SCC-C) had strength of about 50 MPa and the mix with 30% limestone powder replacement (SCC-L30) had strength of about 22MPa, a reduction of 56%, whereas at 91 days the strengths were about 70 and 65MPa respectively; a reduction of only 7%. This shows that that the inclusion of limestone powder can lead to improvements in the rate of hydration reaction as mentioned in 2.4.3. However, contradictory to what was expected there were no improvements in the early-age strength with limestone powder, this could be due to the fact that the starting replacement level of 10% was higher than that for a net strength gain. The mix with 10% limestone powder replacement (SCC-L10) actually obtained higher 91-day strength of 74MPa compared to that of the control mix of about 70MPa.



(a) GGBS



(b) Fly ash



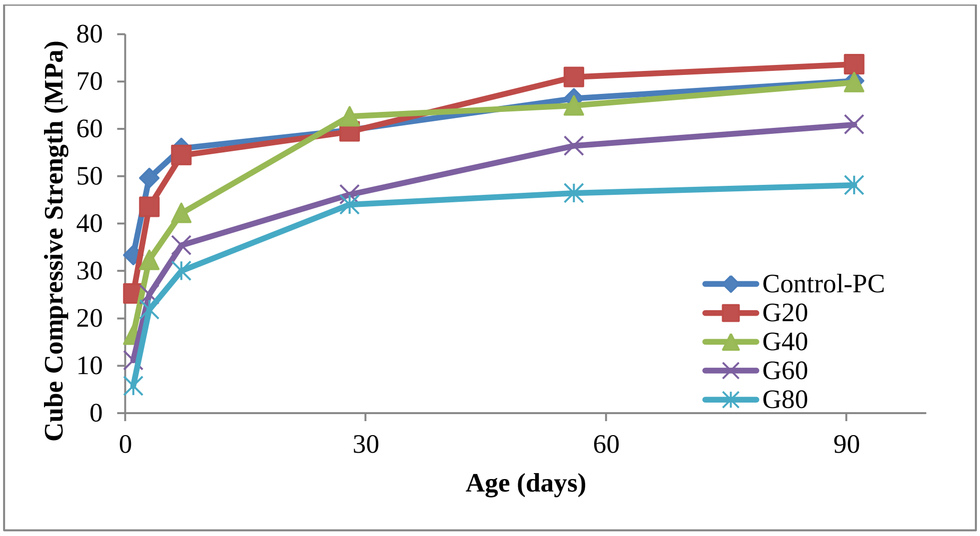
(c) Limestone powder

Figure 7-5 Effect of addition replacement levels on the cube compressive strength of SCC mixes (binary binder)

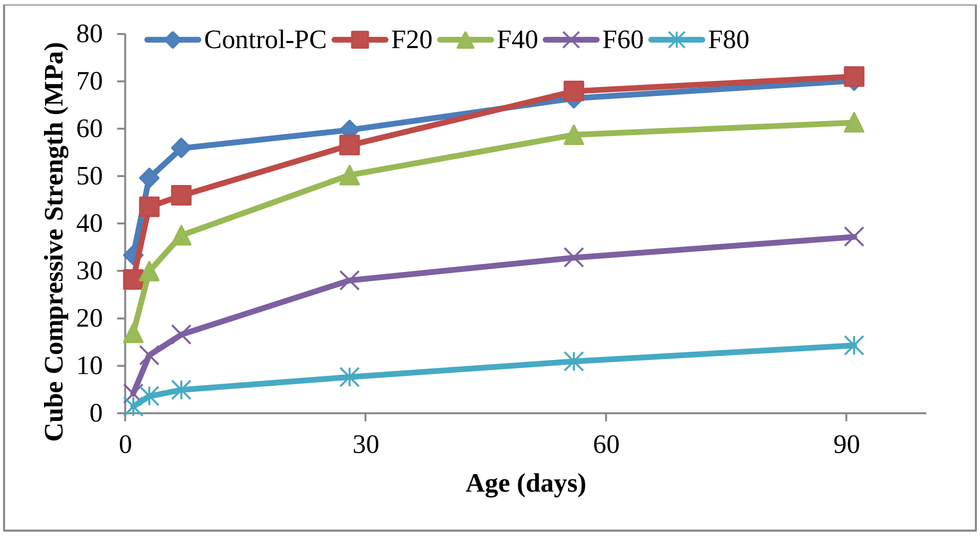
The strength development of the mixes with different additions is shown in Figure 7-6. Improvement in strength with time is apparent and expected, with a sharp rise up to 7 days and a more gradual increase thereafter. The control mix achieved more that 90% of its 28-day strength within the first 7 days, which is slightly faster than a concrete with CEM I 52.5N which can typically be expected to obtain about 75 – 80% of its 28-day strength at 7 days (Domone & Illston, 2010). All mixes with ggbs had a higher rate of strength gain between 7 and 28 days with the mix SCC-G40 (40% ggbs) having the greatest strength gain of 20MPa from 42 to 62MPa at 28 days, similar to the strength attained by the control mix at 28 days (Figure 7-6(a)). The rate of strength gain of mixes SCC-G40 and SCC-G80 was similar to that of the control mix after 28 days however mixes with 20 and 60% ggbs still had a relatively higher rate between 28 and 56 days. This could be attributed the secondary reactions taking place between the ggbs and $Ca(OH)_2$ further contributing to concrete strength.

With fly ash mixes, those with 20, 40 and 60% replacement also showed a higher rate strength gain between 7 and 28 days compared to the control mix, however for the mix with 80% fly ash the rate was lower (Figure 7-6 (b)). The mix SCC-F20 still had a higher rate between 28 and 56 days whilst the others had similar or lower rate of strength gain. As with ggbs, the higher rate of strength gain of the fly ash mixes compared to that of the control mix is a result of the secondary pozzolanic reaction. For both ggbs and fly ash, as with the strength, the rate of strength gain at early ages (<7 days) was lower compared to the control mix and further decreased with increased replacement levels.

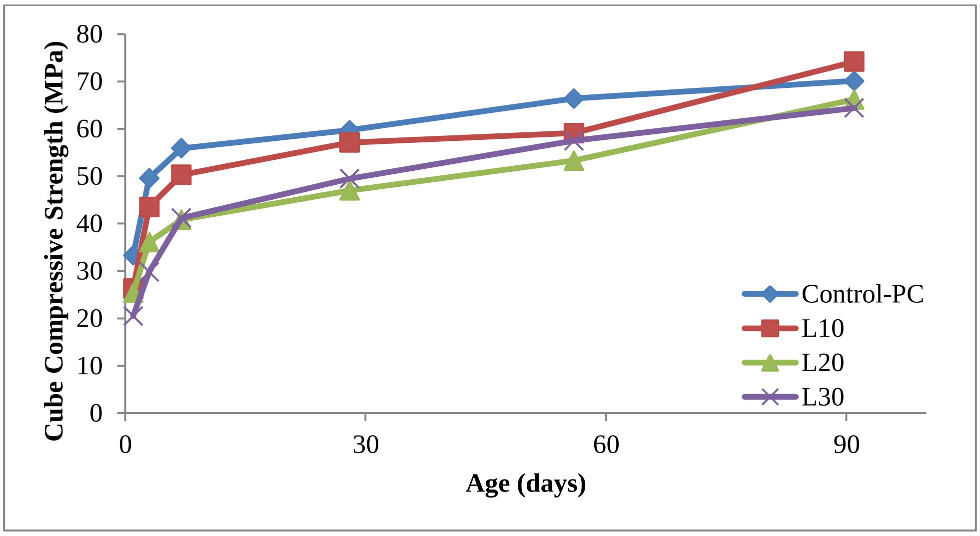
For mixes with limestone powder (Figure 7-6(c)), the mix with 10% limestone powder had a slightly higher rate of strength gain between 1 and 3 days compared to the control mix (18MPa compared to about 16MPa); however this difference is not significant. The mix SCC-L30 (30% limestone powder) had a more distinct increase in the rate between 3 and 7 days (12MPa, about twice that of the control mix); this could be attributed to the better packing increasing the rate of hydration reaction (2.4.3). Overall the difference in compressive strength between the mixes with limestone powder and the control mix seem to decrease with age which means that limestone mixes have on average a higher rate of early-age strength gain which could be attributed to both the physical and chemical advantages offered by limestone powder. The mix with 10% limestone powder (SCC-L10) actually attained a higher strength than the control mix at 91 days.



(a) GGBS



(b) Fly ash



(c) Limestone powder

Figure 7-6 Effect of addition replacement levels on strength development of SCC mixes (binary binder)

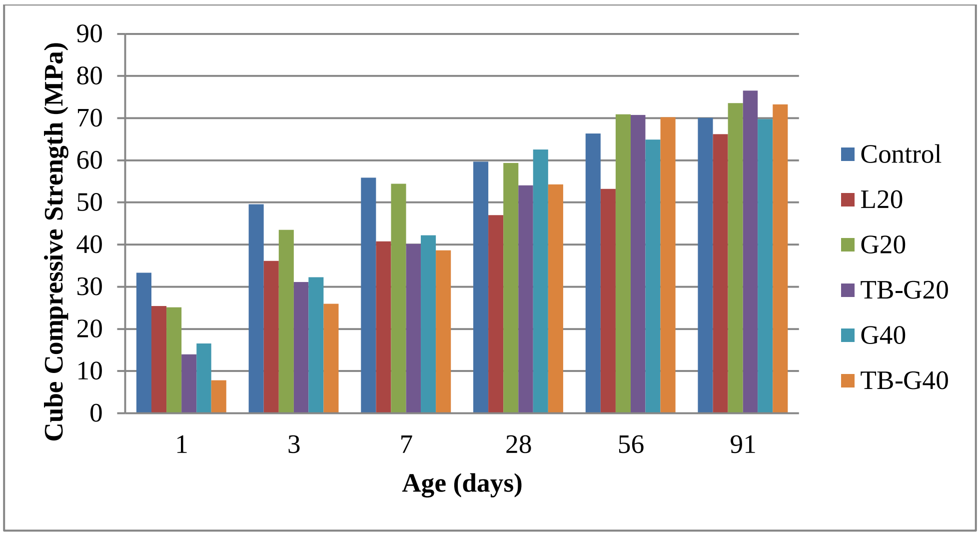
As a general overall trend, the strength of the binary blended binder mixes decreased with increasing replacement levels, for all three addition types (Figure 7-5). This could be explained by the nearly-inert property of limestone powder and the slow hydration rate of ggbs and fly ash at high replacement levels.

7.2.1.2 Ternary binder mixes

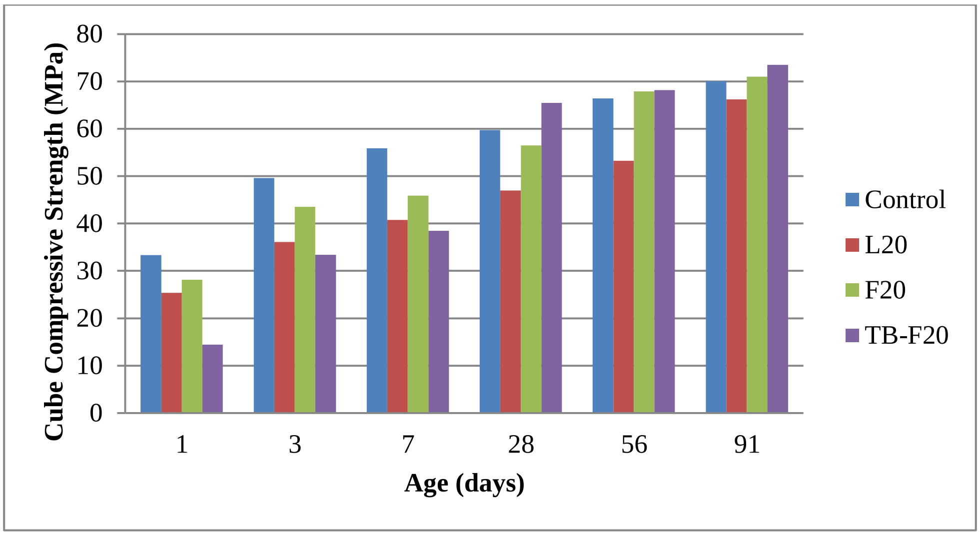
Looking at the performance of the ternary binder mixes in comparison to the control and to their respective binary binder mixes, referring to Table 7-8, it can be seen that some of these mixes attained relatively higher strengths. All the ternary binder mixes had lower compressive strengths at early ages (up to 7 days) compared to both the control and their respective binary binder mixes. This could be attributed to the fact that in the ternary binder blends, the inclusion of limestone powder means less Portland cement available to hydrate.

Looking at the 28-day strength, the ternary binder mix with 60% ggbs (SCC-TB-G60) attained a compressive strength (49.2 MPa) higher than the corresponding binary binder mix SCC-G60 (46.1 MPa) but this is still lower that the control Portland cement mix (59.7 MPa). For ternary binder mixes with fly ash, the mix SCC-TB-F20 (20% fly ash) achieved a strength of 65.5 MPa which is higher than both the binary binder mix SCC-F20 and the control mix which had strengths of 56.5 and 59.7 MPa respectively.

As for the 91-day strength, all the ternary binder mixes with ggbs had a higher strength in comparison to their respective binary binder mixes but with only the mixes SCC-TB-G20 and SCC-TB-G40 achieving strengths (76.6 and 73.3 MPa respectively) higher than the control mix (70.1 MPa). This is illustrated in Figure 7-7 (a). With fly ash, unlike ggbs, only the ternary binder mix with 20% fly ash (SCC-TB-F20) achieved higher strength compared to both the relative binary binder mix and the control mix (73.5 compared to 71 and 70.1 MPa respectively) (Figure 7-7 (b)). This shows that the presence of limestone powder in ternary binder mixes does not compensate for the strength reduction, at early ages, resulting from the use of either ggbs or fly ash, contrary to what was expected, however it does indeed have a positive effect on the long-term strength.



(a)

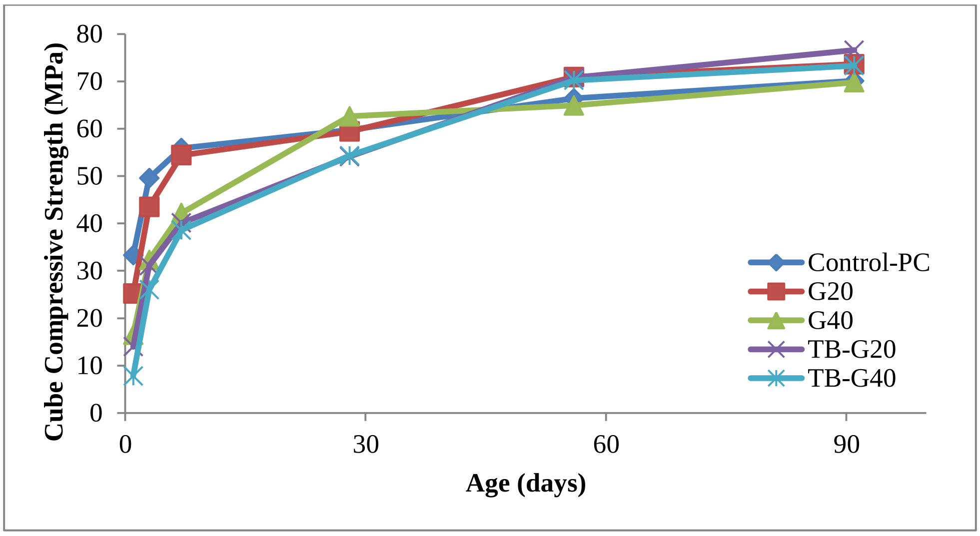


(b)

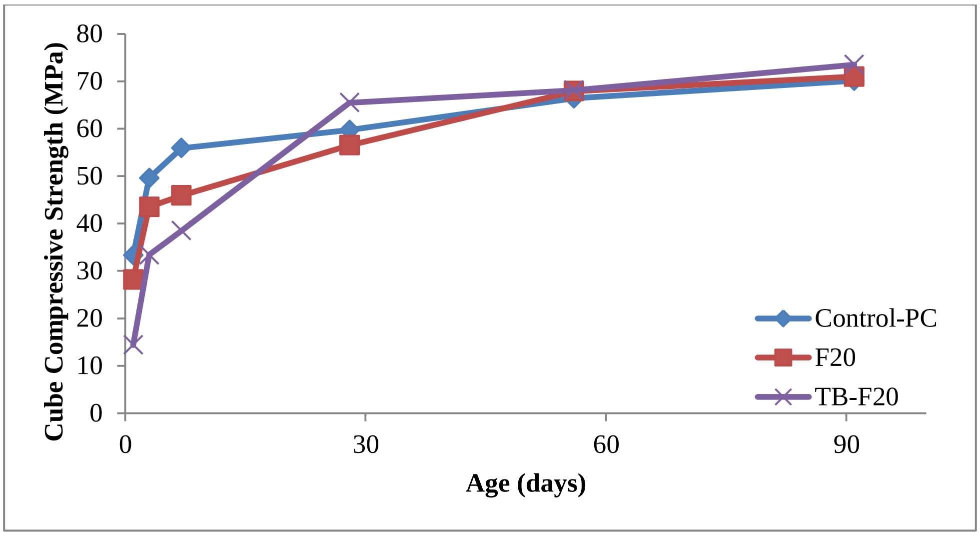
Figure 7-7 Comparison of compressive strength of binary and ternary blended binder mixes with (a) ggbs and (b) fly ash

The strength development of the binary and ternary binder mixes is shown in Figure 7-8. It can be seen in Figure 7-8 (a) that the rate of strength development of the ternary binder mix with 20% ggbs (SCC-TB-G20) is higher than that of the corresponding binary binder mix (SCC-G20) from 7 days onwards. As for the mix with 40% ggbs (SCC-TB-G40), the rate is higher between 3 and 7 days and between 28 and 56 days. It can also be seen that there is minimal difference between the strength development of SCC-TB-G20 and SCC-TB-G40.

As with ggbs, the inclusion of limestone powder also had a positive effect on the rate of strength development of fly ash mixes. In Figure 7-8 (b), comparing the graphs of SCC-F20 and SCC-TB-F20 (binary and ternary mixes with 20% fly ash respectively), it can be seen that between the ages of 3 and 28 days the rate of strength development of SCC-TB-F20 is higher than that of SCC-F20. This increase in the rate of strength development could be attributed to the increase in surface area due to the presence of limestone powder leading to an increased rate of reactions (both the primary hydration reaction and the secondary reactions with ggbs and fly ash).



(a)



(b)

Figure 7-8 Comparison of strength development of binary and ternary blended binder mixes with (a) ggbs and (b) fly ash

7.2.2 Tensile splitting strength

As with the compressive strength, the tensile splitting strength of the concrete mixes increased with age (Table 7-9). As mentioned previously, it has been shown in the literature that the tensile splitting strength of concrete shows a clear relationship with the compressive strength, with the ratio between the two values ranging between 8-10% for normal-strength concrete (Neville, 2011). In this project, the minimum ratio obtained was 6.5% for the ternary binder mix with 20% fly ash (SCC-TB-F20) at 28 days and the maximum ratio was 14.6% for the 28-day strength of binary binder mix with 80% fly ash (SCC-F80). However calculating the average ratio at 28 and 91 days we get 9.3 and 8.7%, giving an overall average of 9% which falls perfectly within the typical range mentioned.

Table 7-9 Tensile splitting strength of SCC mixes

			Tensile splitting strength (MPa)		Tensile splitting strength/Compressive strength ratio (%)	
Binder	**Mix no./Age (days)**		**28**	**91**	**28**	**91**
Control (PC)	1	0%	5.68	6.50	9.5	9.3
Limestone	2	10%	5.02	5.71	8.8	7.7
	3	20%	3.11	4.65	6.6	7.0
	4	30%	4.22	4.70	8.5	7.3
GGBS	5	20%	5.02	5.25	8.5	7.1
	6	40%	5.87	6.27	9.4	9.0
	7	60%	4.84	5.60	10.5	9.2
	8	80%	3.45	4.12	7.8	8.6
Fly Ash	9	20%	4.09	4.98	7.2	7.0
	10	40%	4.28	4.64	8.5	7.6
	11	60%	2.82	2.96	10.1	8.0
	12	80%	1.11	2.04	14.6	14.3
Ternary Binder-GGBS	13	20%	5.09	5.72	9.4	7.5
	14	40%	4.88	5.08	9.0	6.9
	15	60%	4.46	4.76	9.1	7.6
	16	80%	4.10	4.76	9.8	9.5
Ternary Binder- Fly Ash	17	20%	4.25	5.53	6.5	7.5
	18	40%	3.31	4.08	7.9	8.0
	19	60%	2.92	3.97	11.4	11.5
	20	80%	0.86	1.38	12.8	13.5

The Eurocode BS EN 1992-1-1 (EC2) (2004) and the CEB-FIB Model Code 90 (1993) design codes suggest a relationship between these the direct tensile and compressive strength of concrete. Both suggest a ratio between the direct tensile strength to tensile splitting strength of 0.9, hence with these two it was possible to obtain a relationship between the tensile splitting strength and the compressive concrete. These are illustrated in Figure 7-9. These show that the values obtained in this project fall within the range given by both the design codes irrespective of the powder combination used and test age i.e. it is dependent solely on strength. It can also be noticed that majority of the data falls to the right of the EC2 mean line which is in agreement with that obtained by Domone (2007).

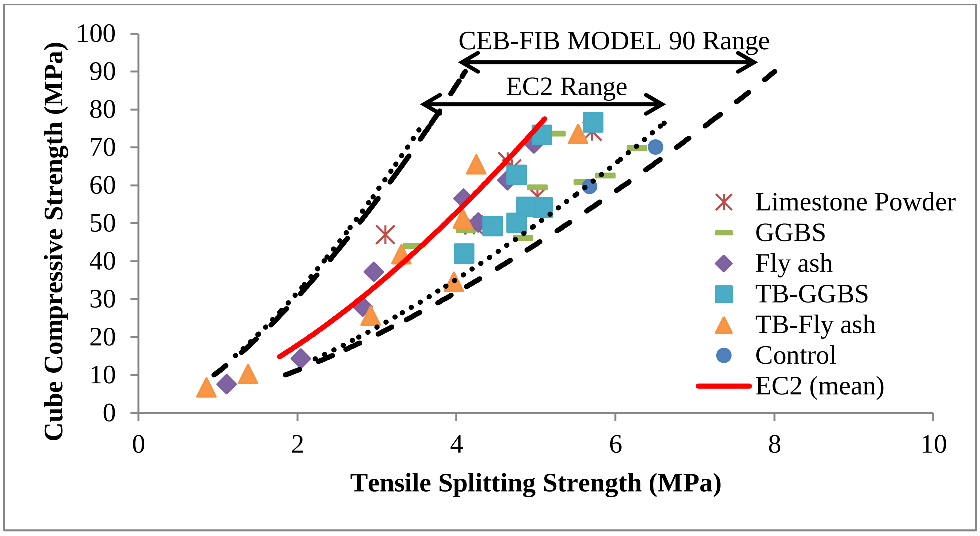


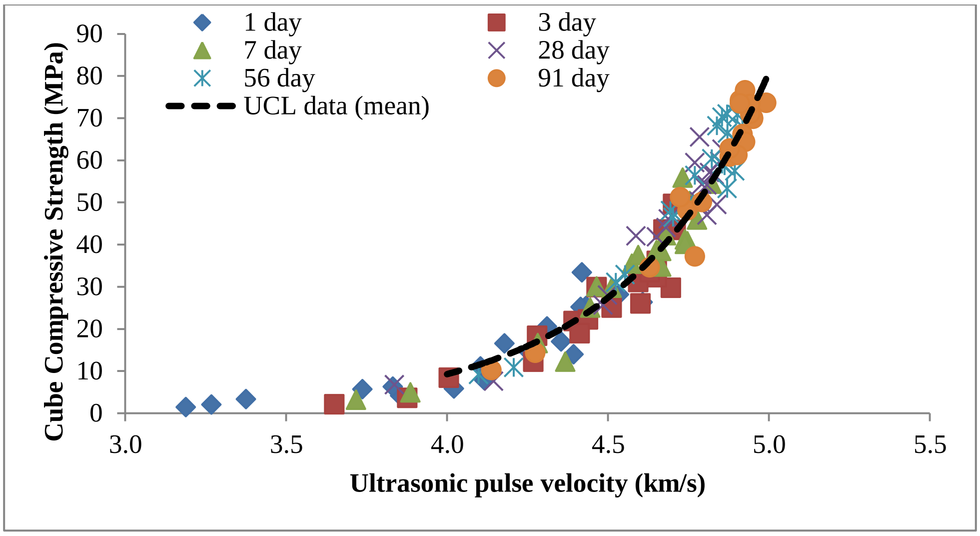
Figure 7-9 Comparison of Compressive strength vs. Tensile splitting strength of SCC mixes with relationships from EC2 and CEB-FIB Model 90

7.2.3 Non-destructive tests

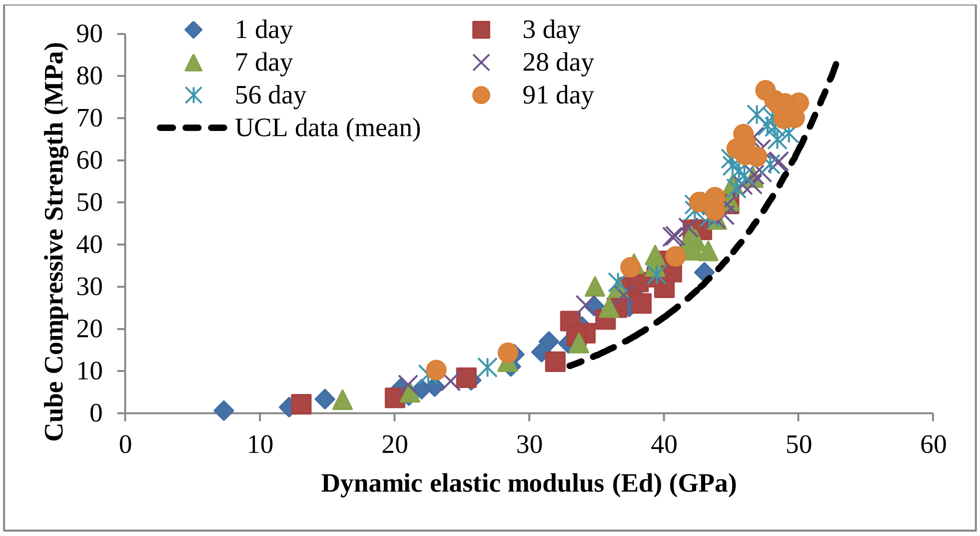
The results of the non-destructive tests showed a similar general trend to the compressive strength results, increasing with age of the specimens and decreasing with increase in replacement level of additions; tabulated results given in Appendix 6. As with the tensile splitting strength, it has been reported in the literature that the results of these tests also have a relationship to the compressive strength of concrete (Neville, 2011; Domone & Illston, 2010). Figure 7-10 (a) and (b) show the results of the current programme and also the relationships from previous studies at UCL obtained with similar aggregate types (Domone & Illston, 2010).

As mentioned previously, the pulse velocity is affected by the density of the concrete and the elastic modulus of component materials (4.4.4), so for a given aggregate type and content, the pulse velocity is primarily affected by the properties of the hardened cement paste, and hence can be used to assess the strength of the concrete, with a higher velocity indicating a stronger concrete. Figure 7-10 (a) shows a clear correlation between the UPV and compressive strength results which is independent of powder composition and testing age, and is very similar to that obtained for normal-consistence concrete at UCL.

The results of dynamic elastic modulus results also have a clear correlation and a similar relationship with compressive strength, again independent of the powder composition and testing age, with the higher strength concrete having a higher dynamic elastic modulus (Figure 7-10 (b)). The difference is that in this case the values are, for a specific compressive strength, consistently lower (by about 5 GPa) than those previously obtained at UCL. The lower values of SCC mixes could be attributed to the lower coarse aggregate content of SCC mixes (around 35% by volume) compared with normal-consistence concrete (around 45% by volume) hence this results in SCC mixes having lower stiffness compared to normal-consistence concrete with the same compressive strength (Domone, 2007). This is also reflected in study by Trtnik et al. (2009).



(a)



(b)

Figure 7-10 Relationship between concrete compressive strength and (a) UPV and (b) dynamic elastic modulus results of SCC mixes

7.3 Effect of additions on durability of self-compacting concrete

As mentioned previously, two durability tests were performed in this project, the sorptivity test and the rapid chloride penetration test. In this section the results of these tests are presented and discussed. Each sorptivity coefficient is an average of three specimens tested whereas the rapid chloride penetration test results are only from a single specimen. The full set of results is given in Appendix 6 andAppendix 7 respectively.

7.3.1 Sorptivity

Again as mentioned previously, the initial water intake is proportional to the square root of time and the sorptivity coefficient is calculated as the rate of change of water intake per unit area with respect to square root of time over the first four hour period of immersion (4.4.5.1). All mixes followed this linear relationship irrespective of powder combination and testing age. For instance the data obtained for the control mix, SCC-G40 and SCC-F40 at 7 days are shown in Figure 7-11 and it can be noticed that the results for all three follow a linear relationship with high degree of correlation (R^2>0.98) and the corresponding sorptivity coefficient is calculated as the gradient of the line, being 0.51, 0.50 and 0.86 kg/m^{2}h$^{0.5}$ respectively for these mixes.

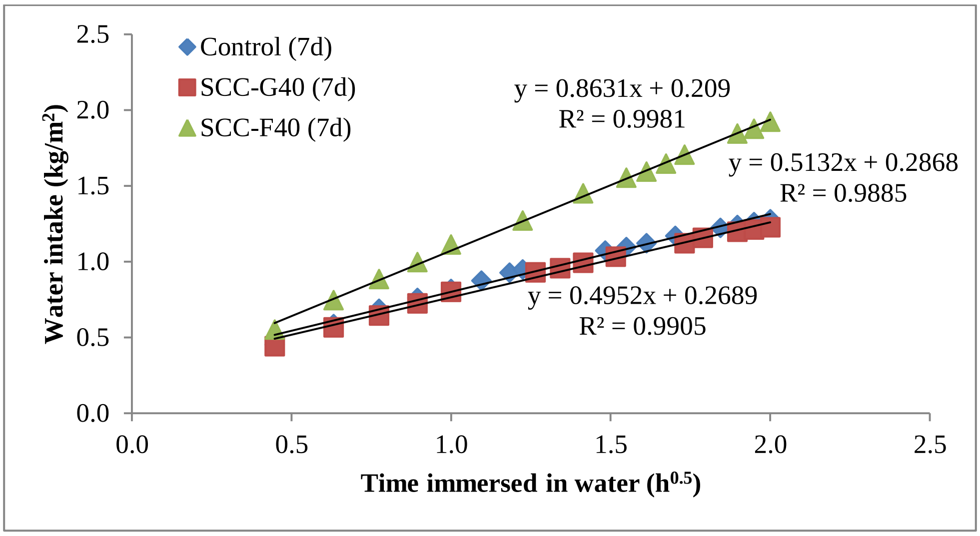


Figure 7-11 Water intake (short-term) vs. square root of time for SCC mixes

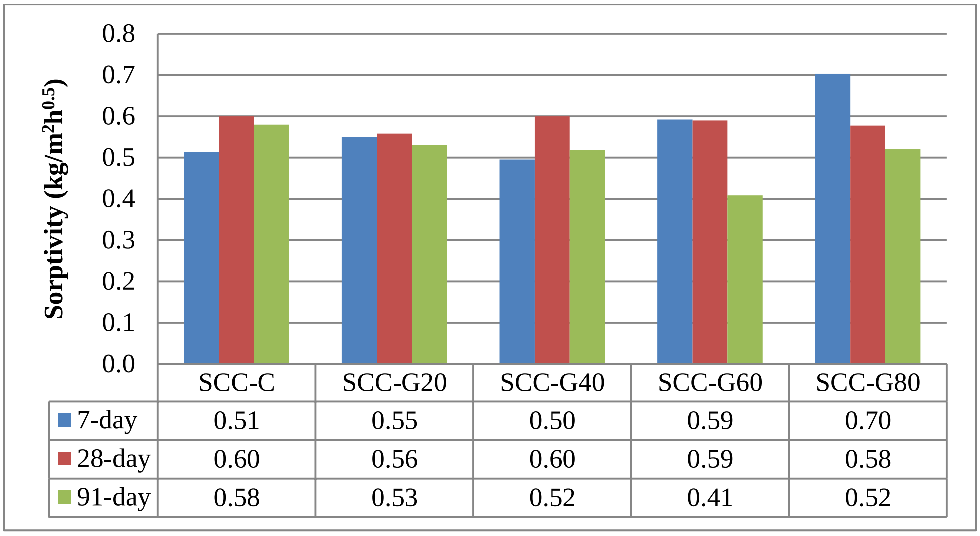
7.3.1.1 Binary binder mixes

The results for the binary binder mixes are shown in Figure 7-12. There is no clear common trend in the coefficients for each addition type with respect to their replacement level and the age of the concrete.

For most ggbs mixes, the sorptivity coefficients seemed to vary only between 0.5 to 0.6 kg/m^{2}h$^{0.5}$ with the exception of the 7-day coefficient of SCC-G60 and the 91-day coefficient of SCC-G80 which were 0.41 and 0.7 kg/m^{2}h$^{0.5}$ respectively (Figure 7-12 (a)). The 91-day value of all the ggbs mixes was lower than that of the control mix. However there does not seem to be a clear trend showing, for the same mix, reduction in sorptivity coefficient with increase in age of concrete as one would expect. For instance with SCC-C, SCC-G20 and SCC-G40 the 28-day coefficient was higher than the corresponding 7-day coefficient with the 91-day coefficient slightly lower than the 28-day value however in the case of SCC-C and SCC-G40 still higher than the 7-day sorptivity coefficient.

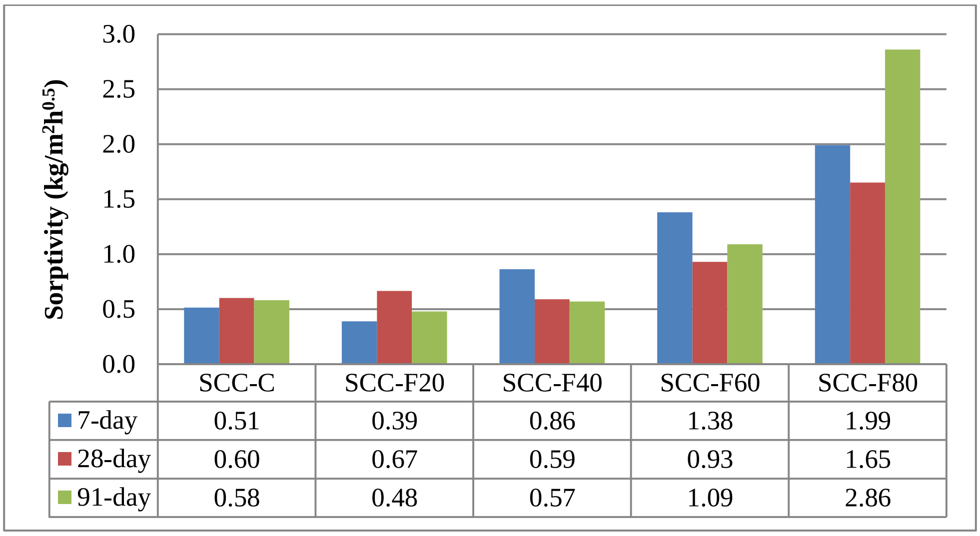
For fly ash mixes, the mix with 20% fly ash (SCC-F20) had the lowest sorptivity coefficient at 7 and 91 days of 0.39 and 0.48 $kg/m^2h^{0.5}$ respectively compared to other fly ash mixes and also the control mix which had coefficients of 0.51 and 0.58 $kg/m^2h^{0.5}$ respectively (Figure 7-12 (b)). It can be noticed that there is no drastic change in the coefficients up to 40% replacement level with a more significant increase seen for the HVFA mixes with 60 and 80% fly ash replacement levels.

Unlike the results obtained for ggbs and fly ash mixes, the mixes containing limestone powder showed a clear decrease in sorptivity coefficient with increase in age of concrete. All the mixes had a higher 7 and 28-day sorptivity coefficient compared to the control mix (Figure 7-12 (c)). Similar trend was obtained by Ramezanianpour et al. (2009) for the 28-day sorptivity coefficients. The mix with 10% limestone powder replacement (SCC-L10) had higher 91-day coefficient (0.88 $kg/m^2h^{0.5}$) than the control mix (0.58 $kg/m^2h^{0.5}$). Further increase in replacement level resulted in decrease in the 91-day coefficient; the mix SCC-L20 (20% replacement level) had a similar coefficient as the control mix whereas a further 10% increase in replacement level (SCC-L30) resulted in coefficient of 0.28 $kg/m^2h^{0.5}$ which is lower than that of the control mix. As mentioned, here the sorptivity coefficients decrease with increase in age of concrete as one would expect but in addition the drop in sorptivity coefficient from 7 to 91 days increases with increase in replacement level; the mix with 10% limestone powder replacement had a 25% decrease whereas the decrease in mixes with 20 and 30% limestone powder replacement was about 57 and 80% respectively.



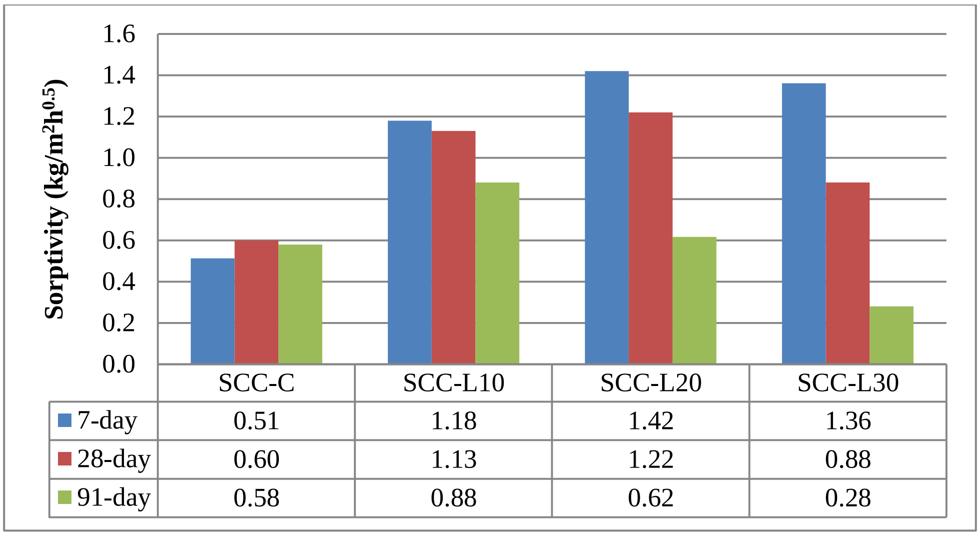
	SCC-C	SCC-G20	SCC-G40	SCC-G60	SCC-G80
🟦 7-day	0.51	0.55	0.50	0.59	0.70
🟥 28-day	0.60	0.56	0.60	0.59	0.58
🟩 91-day	0.58	0.53	0.52	0.41	0.52

(a) GGBS



	SCC-C	SCC-F20	SCC-F40	SCC-F60	SCC-F80
🟦 7-day	0.51	0.39	0.86	1.38	1.99
🟥 28-day	0.60	0.67	0.59	0.93	1.65
🟩 91-day	0.58	0.48	0.57	1.09	2.86

(b) Fly ash



(c) Limestone powder

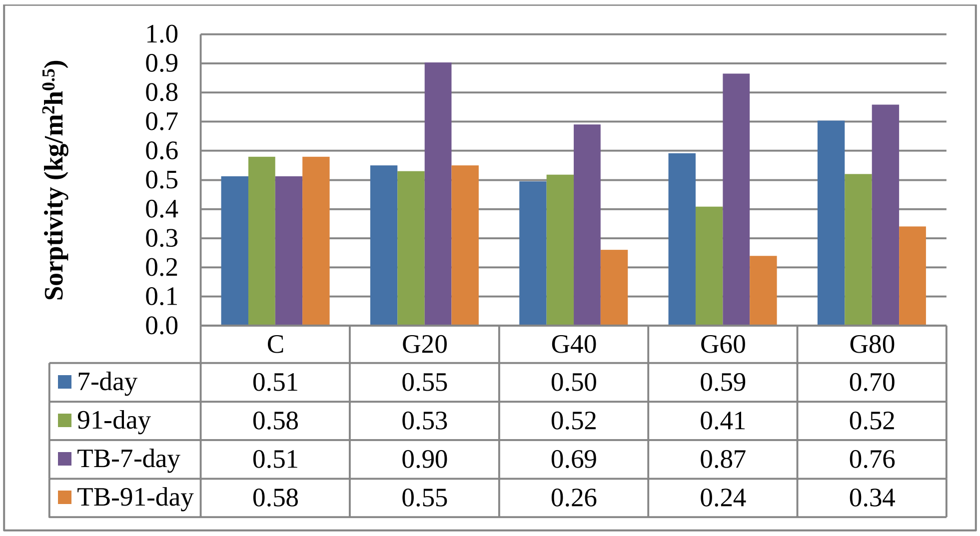
Figure 7-12 Sorptivity coefficient (short-term) of SCC mixes with binary blended binders

7.3.1.2 Ternary binder mixes

The 7 and 91-day sorptivity results obtained for the ternary binder concretes are shown in Figure 7-13. The 28-day sorptivity results are not shown here as it was decided that the 7 and 91-day results were sufficient to give an indication of the sorptivity at early and later ages respectively.

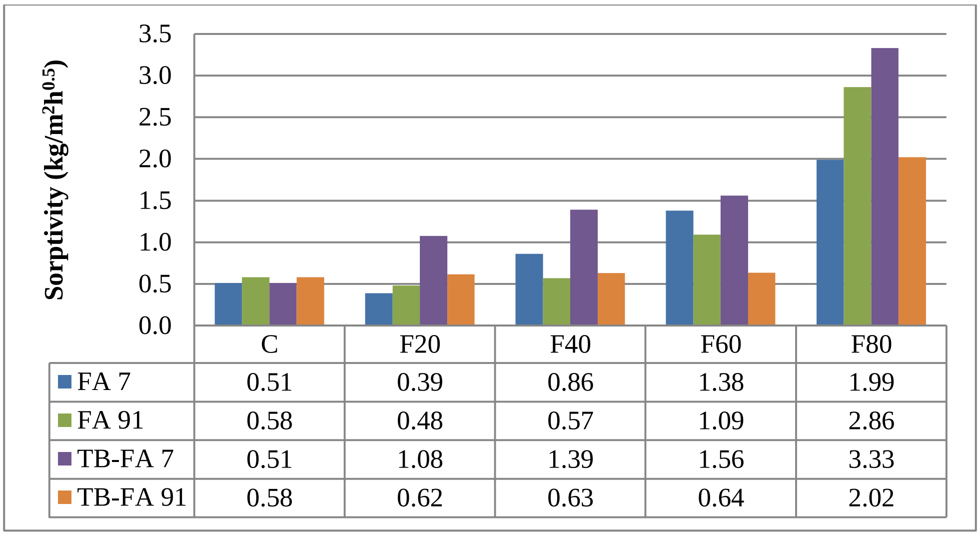
The 7-day sorptivity coefficient of the ternary binder mixes, both with ggbs and fly ash, were higher than their respective binary binder mixes at all replacement levels. For example comparing the mixes with 40% replacement level, the coefficients for the binary and ternary binder mixes with ggbs was 0.5 and 0.69 kg/m^{2}h$^{0.5}$ and similarly for the fly ash mixes it was 0.86 and 1.39 kg/m^{2}h$^{0.5}$ respectively. On the other hand the 91-day sorptivity coefficients of all the ternary binder mixes with ggbs and the HVFA mixes (60 and 80% fly ash replacement) were similar or lower than that of their respective binary binder mixes. Hence by using ternary binder mixes with limestone powder it is possible to achieve concrete with similar or superior long-term performance with a higher replacement level resulting in both economic (reduced cost) and environmental advantages (reduced carbon footprint); this is further discussed in Chapter 9.

With the inclusion of limestone powder, to start with there is less Portland cement available to hydrate hence a less dense matrix is formed resulting in the higher sorptivity coefficients at early ages (7-day). However over time the advantages offered by presence of limestone powder i.e. better packing and heterogeneous nucleation (2.4.3), increase the rate of primary hydration reaction and consequently the secondary reactions with fly and ggbs resulting in the formation of an even denser matrix compared to binary binder mixes hence the lower long-term (91-day) sorptivity coefficients. As mentioned previously, the binary binder mixes with limestone powder had a significantly higher decrease in sorptivity coefficient from 7 to 91 days compared to ggbs and fly ash mixes. This effect can also be observed in the ternary binder mixes where the decrease in sorptivity coefficient from 7 to 91 days is significantly higher than that of their respective binary binder mix. For instance for ggbs, the decrease for the binary and ternary binder mixes with 60% replacement were 30 and 72% respectively and similarly for fly ash, for the same replacement level the decrease were 21 and 59% respectively.



	C	G20	G40	G60	G80
🟦 7-day	0.51	0.55	0.50	0.59	0.70
🟩 91-day	0.58	0.53	0.52	0.41	0.52
🟪 TB-7-day	0.51	0.90	0.69	0.87	0.76
🟧 TB-91-day	0.58	0.55	0.26	0.24	0.34

(a)



	C	F20	F40	F60	F80
■ FA 7	0.51	0.39	0.86	1.38	1.99
■ FA 91	0.58	0.48	0.57	1.09	2.86
■ TB-FA 7	0.51	1.08	1.39	1.56	3.33
■ TB-FA 91	0.58	0.62	0.63	0.64	2.02

(b)

Figure 7-13 Sorptivity coefficient (short-term) of SCC mixes with ternary blended binders

There is a good correlation (R^2=0.713) between the sorptivity coefficient and the cube compressive strength, as shown in Figure 7-14, independent of the concrete age and powder combination. This shows that the higher the compressive strength, the lower the sorptivity coefficient. The change in sorptivity is more profound at lower strength (< 30MPa) and less so for higher strengths. For strengths greater than 30MPa, it can be noticed that the coefficients lie between 0.5 – 1 kg/m^{2}h$^{0.5}$. Referring back to Figure 7-8, the compressive strength of concrete continues to increase with age so the longer the curing period, more hydration products are produced forming a finer internal pore structure and denser matrix; this results in the concrete mix having a higher compressive strength and the finer and denser pore structure makes it more difficult for liquids to enter the concrete hence the lower sorptivity coefficient. Similar values of sorptivity coefficient, as shown in Figure 7-14, were obtained by Zhu & Bartos (2003) and Assie et al. (2006). The results also follow a similar trend to that observed in this project. Kanellopoulos et al. (2012) also found a similar trend however the sorptivity values were reported in different units (mm/min$^{0.5}$) to this project; as a comparison, the sorptivity coefficient obtained for 60MPa was about 0.075 mm/min$^{0.5}$ and in this project it is about 0.077 mm/min$^{0.5}$.

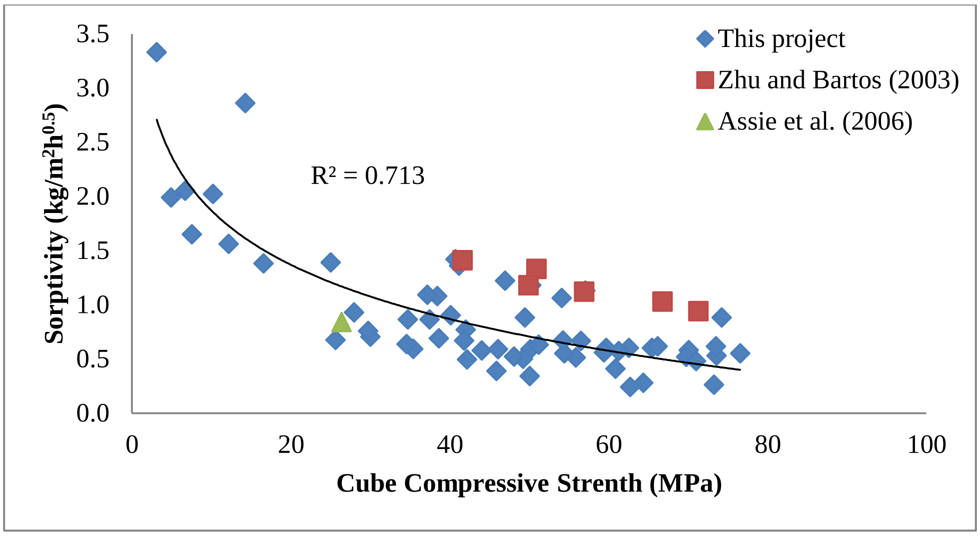


Figure 7-14 Relationship between sorptivity coefficient (short-term) and the cube compressive strength of SCC mixes

7.3.2 Rapid chloride penetration test

In the rapid chloride penetration tests, the total amount of charge passed reduced with age for all mixes (Table 7-10 and Figure 7-15), thus showing different trends to the sorptivity results. As mentioned above, as the concrete matures, with continuous hydration reaction taking place, a denser matrix is formed making it more difficult for ions to penetrate the concrete. The standard deviation for this test is given as 12.3% in ASTM C1202 (2007), hence the corresponding repeatability value would be around 34% (for 95% confidence level), hence any difference less than that might not be significantly different.

Table 7-10 Rapid chloride penetration test results for SCC mixes

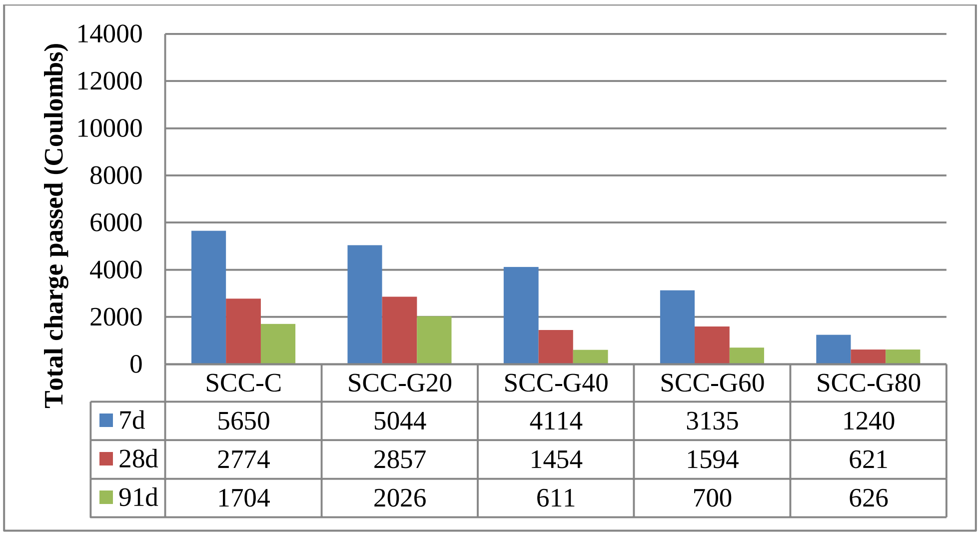
			Total charge passed (Coulombs)			**Rating according to ASTM C1202** (2007)		
Binder	**Mix no./Age (days)**		**7**	**28**	**91**	**7**	**28**	**91**
Control (PC)	1	0%	5650	2774	1704	High	Moderate	Low
Limestone	2	10%	8806	3636	2603	High	Moderate	Moderate
	3	20%	12180	10090	4929	High	High	High
	4	30%	5486	4712	2513	High	High	Moderate
GGBS	5	20%	5044	2857	2026	High	Moderate	Moderate
	6	40%	4114	1454	611	High	Low	Very Low
	7	60%	3135	1594	700	Moderate	Low	Very Low
	8	80%	1240	621	626	Low	Very Low	Very Low
Fly Ash	9	20%	5762	2403	585	High	Moderate	Very Low
	10	40%	9206	2701	793	High	Moderate	Very Low
	11	60%	8333	2283	1056	High	Moderate	Low
	12	80%	7548	4560	3205	High	High	Moderate
Ternary Binder-GGBS	13	20%	7257	3491	2347	High	Moderate	Moderate
	14	40%	2237	1448	990	Moderate	Low	Very Low
	15	60%	829	573	446	Very Low	Very Low	Very Low
	16	80%	371	362	227	Very Low	Very Low	Very Low
Ternary Binder- Fly Ash	17	20%	9821	1839	1223	High	Low	Low
	18	40%	9454	1903	951	High	Low	Very Low
	19	60%	10570	2750	1009	High	Moderate	Low
	20	80%	11500	3290	2878	High	Moderate	Moderate

7.3.2.1 Binary binder mixes

For mixes with ggbs, the total amount of charge passed at 7 days decreased, rather steadily, with the increase in replacement level (Figure 7-15 (a)). However, considering a repeatability value of 34%, the difference in values of charge passed between the mixes up to 60% replacement level is not large enough hence they might not be significantly different. The mix with 80% replacement level (SCC-G80) had a significantly lower value of charge passed compared to the other mixes. Looking at the 28 and 91-day results, it can be noticed that the mix with 20% ggbs (SCC-G20) had similar values of charge passed as the control mix. Unlike the steadily decrease at 7 days, in this case there was a significant drop in the charge value when the replacement is increased from 20 to 40%. The mixes with 40, 60 and 80% ggbs gave similar values of charge passed at both 28 and 91 days; all lower than that of SCC-G20 and the control mix. Considering the 91-day values of charge passed, the control mix and the mix SCC-G20 attained values of 1704 and 2026 Coulombs respectively giving them a rating, according to ASTM C1202 (2007) (Figure 7-16), of “Low” and “Moderate” respectively. Similarly the mixes with 40, 60 and 80% ggbs attained values of 611, 700 and 626 Coulombs respectively, all attaining a rating of “Very Low” indicating better chloride resistance. This could be attributed to the secondary reaction with ggbs producing a denser matrix.

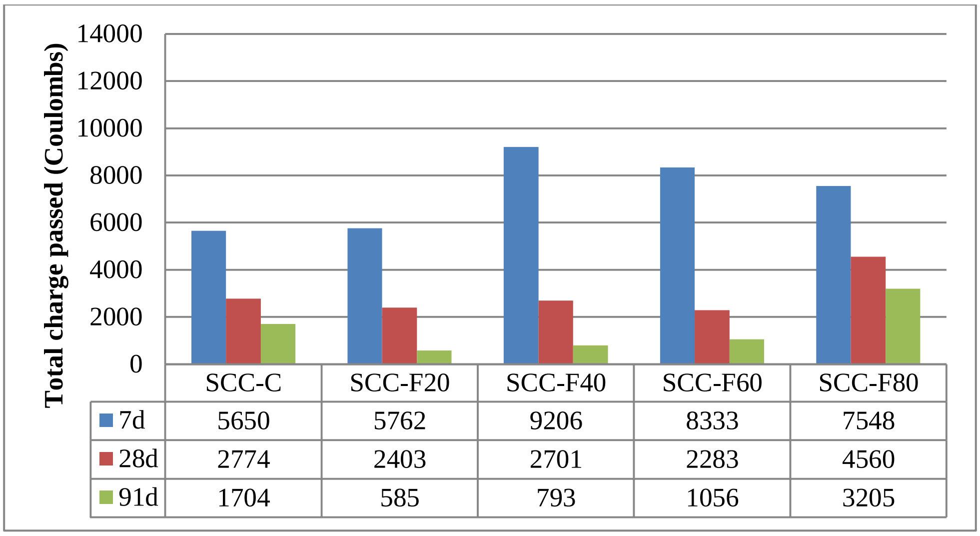
The addition of 20% fly ash did not seem to have much influence on the total charge passed at 7 days as it had a similar value as the control mix. Increasing the replacement level to 40% resulted in a large increase of about 60% (Figure 7-15 (b)). Further increasing the replacement level to 60 and 80% resulted in a reduction in the magnitude of total charge passed, however none of these differences were large enough to make them significant. At 28 days, the mixes with 20, 40 and 60% fly ash gave similar values to the control mix, ranging between 2000 and 3000 Coulombs, obtaining a “Moderate” rating. The mix with 80% replacement attained a relatively higher value of about 4560 Coulombs giving it a rating of “high”, however, similar to the 7-day results, these differences were still not large enough to make these results significantly different. On the other hand, in the long-term (91 days) all the fly ash mixes up to 60% replacement level attained values significantly lower than that of the control mix; all attaining ratings of “Low” and “Very Low”, with the 20% fly ash mix (SCC-F20) obtaining the lowest charge passed of 585 Coulombs. The mix with 80% fly ash again was worse off, this time attaining a significantly higher value of charge (3205 Coulombs) compared to other fly ash mixes, albeit similar to that attained by the control mix. Also the mix with 40% fly ash (SCC-F40) had the greatest difference in values of charge passed from 7 to 91 days, decreasing from 9000 to about 800 Coulombs. As with ggbs, the superior long-term performance of these mixes can be attributed to the secondary pozzolanic reaction with fly ash producing further cementitious compounds resulting in the formation of denser matrix.

The mixes with 10 and 20% limestone powder replacement gave a significantly higher value of charge passed at 7 days compared to the control mix, whereas the mix incorporating 30% limestone powder attained similar value. At 28 days similar values were obtained for the mix with 10% limestone powder (SCC-L10) and the control mix, however increasing the replacement level to 20% resulted in a significant increase in the value of charge from 3636 to 10090 Coulombs respectively, almost three times higher. A further 10% increase in the replacement level caused the total charge to halve, making it similar to that of SCC-L10. At 91 days, as with the 28-day results, the mixes with 10 and 30% limestone powder gave similar values of charge passed with both being higher than that of the control mix. The former two mixes attained ratings of “Moderate” whereas the control mix got a rating of “Low”. The mix with 20% limestone powder replacement again gave a significantly higher value of charge, as with the 7 and 28-day results, with its rating still being “High” making it highly permeable to ion penetration even at 91 days.

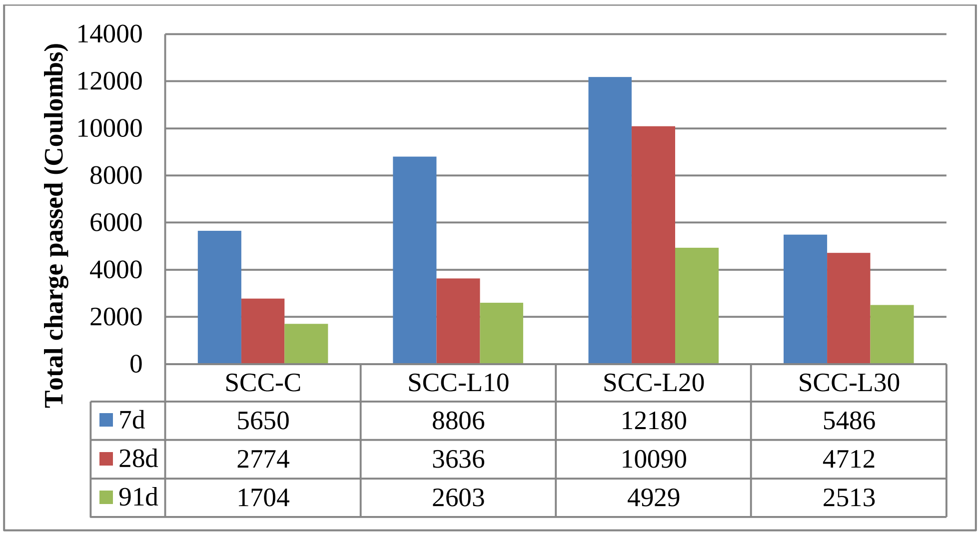


	SCC-C	SCC-G20	SCC-G40	SCC-G60	SCC-G80
🟦 7d	5650	5044	4114	3135	1240
🟥 28d	2774	2857	1454	1594	621
🟩 91d	1704	2026	611	700	626

(a) GGBS

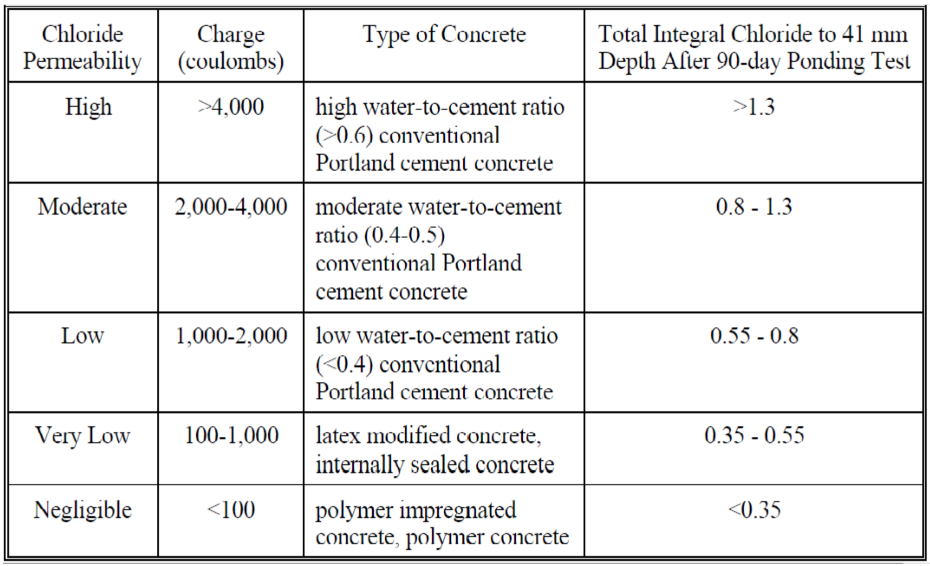


(b) Fly ash



(c) Limestone powder

Figure 7-15 Total charge passed of SCC mixes with different additions



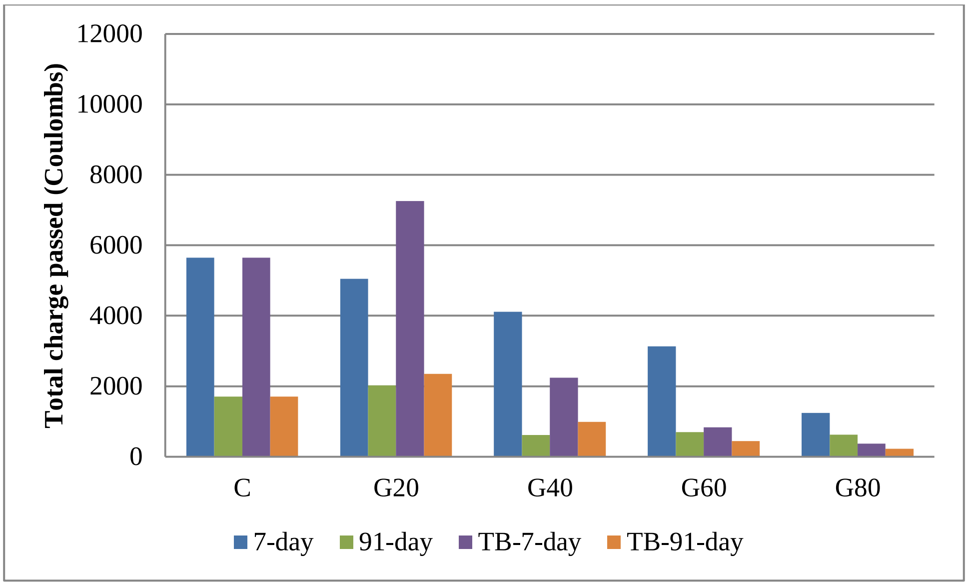
Chloride Permeability	Charge (coulombs)	Type of Concrete	Total Integral Chloride to 41 mm Depth After 90-day Ponding Test
High	>4,000	high water-to-cement ratio (>0.6) conventional Portland cement concrete	>1.3
Moderate	2,000-4,000	moderate water-to-cement ratio (0.4-0.5) conventional Portland cement concrete	0.8 - 1.3
Low	1,000-2,000	low water-to-cement ratio (<0.4) conventional Portland cement concrete	0.55 - 0.8
Very Low	100-1,000	latex modified concrete, internally sealed concrete	0.35 - 0.55
Negligible	<100	polymer impregnated concrete, polymer concrete	<0.35

Figure 7-16 Rating scale according to ASTM C1202 (2007) **for RCP test**

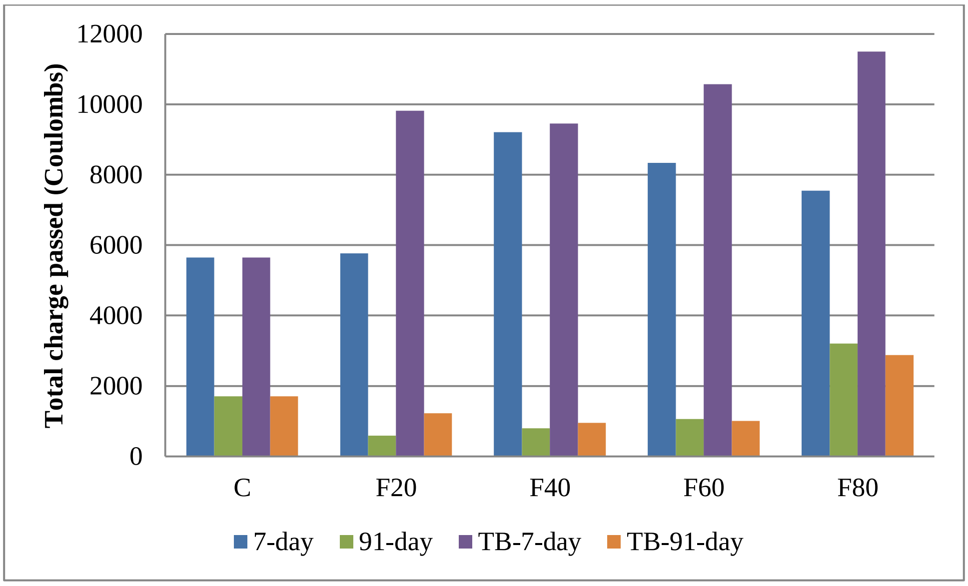
7.3.2.2 Ternary binder mixes

Moving on to mixes with ternary blended binders, referring to Figure 7-17 (a), we can see that for the mix with 20% ggbs replacement level the 7-day charge passed was higher than the corresponding binary mix and the control mix whereas for mixes with 40, 60 and 80% replacement levels the charge passed was lower compared to both the control and corresponding binary binder mixes. For mixes with 20 and 40% ggbs, the difference in values of charge passed at 7 days between the binary and ternary binary mixes was not large enough to be significant given the high repeatability value of this test. On the contrary, the ternary binder mixes with 60 and 80% ggbs gave significantly lower values of charge passed compared to their respective binary binder mixes. Similarly for the test results at 91 days, there was a slight difference in the magnitudes of charge between the binary and ternary binder mixes, with the ternary binder mixes with 20 and 40% ggbs giving slightly higher values and mixes with 60 and 80% ggbs giving slightly lower values, however in this case only the ternary binder mix with 80% ggbs gave a significantly lower value of charge passed. As with their corresponding binary mixes, the ternary binder mixes with 40, 60 and 80% ggbs replacement all obtained a charge passed of less than 1000 Coulombs giving then a rating of “Very Low”. Looking at the high replacement levels of 60 and 80%, the 91-day ternary binder mixes actually gave lower values of charge passed compared to their respective binary binder mixes which could be attributed to the influence of limestone powder giving a better packing and increasing the rate of both the primary hydration reaction and the secondary reaction with ggbs resulting in the formation of a denser matrix in the long-term. Overall this has shown that it is possible to achieve, with the incorporation of limestone powder, mixes with similar or better performance which is an advantage as the replacement levels are higher; this is discussed further in Chapter 9.

Unlike ggbs, all the ternary binder fly ash mixes attained similar values of charge as their respective binary binder mixes at both 7 and 91 days. As with ggbs, there were differences in the magnitudes of charge passed between the binary and ternary binder mixes; however these were not large enough to be significant (Figure 7-17 (b)). Looking only at the magnitudes only, it can be noticed that all the ternary binder mixes had a higher value of charge passed at 7 days, whereas at 91 days, only the mix with 20% fly ash had a higher value with the other attaining similar or lower values. Looking at the 91-day results, the mix with 80% fly ash replacement performed poorly giving a significantly higher value of charge compared to other fly ash mixes; similar to the sorptivity results. Overall only the ternary binder mix with 40% fly ash obtained a 91-day rating of “Very Low” with the mixes with 20 and 60% replacement obtained ratings of “Low” though their value were only slightly over the 1000 Coulombs upper boundary of the “Very Low” rating standing at 1223 and 1009 Coulombs respectively. Unlike ggbs, the inclusion of limestone powder with fly ash did not seem to have a major impact on the 91-day values of charge passed. Usually an arbitrary value of less than 1000 Coulombs is specified by engineers for structural concrete (Bentz, 2007; Pfeifer et al., 1994) corresponding to a “Very Low” rating.



(a)



(b)

Figure 7-17 Total charge passed for SCC mixes with ternary blended binders

Unlike the sorptivity test, there seems to be no correlation between the total charge passed and the cube compressive strength (Figure 7-18). A similar conclusion was obtained by Rohne (2009).

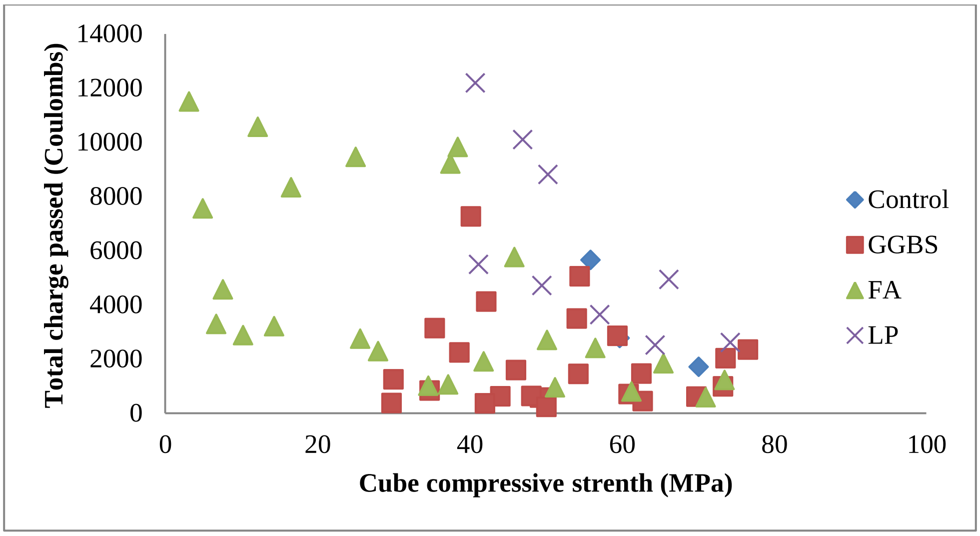


Figure 7-18 Correlation between the RCP test results and cube compressive strength of SCC mixes

7.4 Conclusions

In this chapter the results of the tests on fresh and hardened properties of SCC mixes with binary and ternary blended binders containing different levels of ggbs, fly ash and limestone powder, have been presented. All the cement replacements were by volume. The concluding remarks drawn from this investigation are given in this section.

1. <u>Tests on mortar fraction of SCC</u>

- Tests on the mortar fractions of SCC with various replacement levels of additions showed that, for all three powders, the V-funnel time decreases with increasing level of addition. The influence of fly ash on V-funnel time was greater than that of ggbs; a decrease of 4 seconds compared to 1.5 seconds respectively.

- For ggbs mixes, the maximum spread value was achieved at 40% replacement and stayed constant at 60 and 80% replacement however the halo thickness increased (excess bleeding) by about 20mm during this increase; from 15mm for 40% to 35mm for 80% replacement. Similarly for fly ash mixes, the maximum spread value was achieved at 40% replacement however, surprisingly, decreased with higher replacement levels and the halo thickness increased from 10 to 17mm for 40 and 80% replacement level. Fly ash mixes had a smaller halo compared to ggbs mixes however the reduction in retained water ratio of fly ash is greater than with ggbs hence making the results inconsistent in this respect. All three fineness of limestone powder tested resulted in an increased spread value with increasing replacement level with the exception of mortar mix with 10% B45 limestone powder. A 25/75% combination of B45/B10 limestone powder was used in all mixes as it gave lowest retained water ratio.

- Obtaining the target mortar properties required a decrease in superplasticiser dosage and in some cases, for stability and eliminating bleeding, addition of a viscosity modifying agent. This was used to achieve the target SCC mixes, with slight adjustments to the admixture dosages if necessary, for all the different addition levels.

- With the rheological properties, a good correlation exists between the plastic viscosity and the V-funnel time for both mortar (Figure 6-6) and concrete mixes (Figure 7-4).

2. Strength tests on SCC mixes

Binary binder mixes

- For all three additions, there was a reduction in the early-age strengths with increasing replacement levels. As for the long-term strength, the mixes with 40% ggbs, 20% fly ash and 10% limestone powder replacement attained similar, albeit slightly higher, 91-day strength as the control mix. For All additions, the percentage reduction in strength was greater at early ages than later ages, indicative of higher rate of strength gain.

- The optimum replacement levels for ggbs and fly ash were 40 and 20% respectively (binary binder) as these were the highest replacement levels for which the mixes attained similar or higher long-term strengths to the control mix.

Ternary binder mixes

- The ternary binders comprised a 4:1 combination of Portland cement and limestone powder as the primary binder which was then replaced with the required percentage of ggbs and fly ash. All the ternary binder mixes had a lower early-age strength compared to their respective binary binder mixes. The mixes with 40% ggbs and 20% fly ash attained a slightly higher 91-day strength compared to both the control mix and their respective binary binder mix. This could be indicative of synergistic effects of the limestone powder with ggbs and fly ash. Mixes with higher replacement levels of ggbs i.e. 60 and 80% attained higher strength compared to their binary binder mix however lower than the control mix. On the contrary, fly ash mixes with 40, 60 and 80% replacement attained strengths lower than both their respective binary binder and the control mix. Hence, as with the binary binder mixes, the optimum replacement levels of ggbs and fly ash are 40 and 20% respectively.

- Good correlations were obtained between the cube compressive and tensile splitting strength of concrete, with the results falling within the ranges given by Eurocode 2 and CEB-FIB Model 90 design codes for normal-consistence concrete. Good correlations were also obtained between the cube compressive strength and the results of the non-destructive tests. The UPV results had a good fit with a typical correlation given in the literature for normal-consistence concrete; however the dynamic elastic modulus results, although following the same trend, were lower than those in a typical correlation. This could be due to the lower coarse aggregate content of SCC compared to normal-consistence concrete.

3. Durability tests on SCC mixes

- For binary blended binder mixes, the addition of ggbs did not have any significant effect on the sorptivity; the coefficients ranged only between 0.4 – 07 kg/m^{2}h$^{0.5}$ with most being between 0.5 – 0.6 kg/m^{2}h$^{0.5}$.

  The sorptivity of mixes with up to 40% fly ash were similar but increased significantly for HVFA mixes. The 91-day coefficient of the mix with 80% fly ash was around five times higher than the mix with 40% fly ash.

  The 7-day sorptivity coefficient for mixes with limestone powder were all higher than the control mix, however the 91-day coefficient for mixes with 20 and 30% replacement were similar and lower respectively compared to that of the control mix. Limestone powder mixes also showed the largest change in sorptivity coefficient between 7 and 91 days.

- All the ternary blended binder mixes had a higher 7-day sorptivity coefficient than both the control mix and their respective binary binder mixes. For ggbs mixes, the 91-day sorptivity coefficients were all lower than the control mix but also, for mixes with 40, 60 and 80% replacement, it was lower than their respective binary binder mix.

  Fly ash mixes with up to 60% replacement had similar sorptivity to the control mix at 91 days with significant increase (three times) when replacement increased to 80%. The HVFA mixes, with 60 and 80% fly ash, attained 91-day coefficients lower than their binary binder mix.

- For ggbs and fly ash mixes there was no obvious trend between the sorptivity coefficients and age of concrete; however a good correlation was obtained with the cube compressive strength ($R^2 = 0.713$).

- Binary binder mixes with ggbs with replacement levels of 40% and above had lower values for total charge passed in the RCP test at all ages compared to the control mix, with the 40% replacement having the lowest value for charge passed at 91 days.

All the fly ash mixes had similar values of charge passed to the control mix at 7 days. Mixes with up to 60% replacement had similar and lower values of charge to the control mix at 28 and 91 days respectively, higher replacement resulted in significant increase in charge value. The mix with 20% replacement had the lowest value of charge passed at 91 days.

The mix with 10 and 30% limestone powder had similar value of charge passed as the control mix at 28 and 91days. The mix with 20% limestone replacement had higher values at all ages.

- The ternary binder mix with 20% ggbs had a similar charge passed at 7 days whereas the mixes with replacement levels of 40% and higher had lower values compared to both the control mix and the binary binder mix. As with the binary binder mixes, ternary binder mixes with ggbs replacement of 40% or higher attained lower values of charge at 91 days compared to the control mix. All mixes up to 60% replacement attained similar values of charge compared to their respective binary binder mix with only the mix with 80% ggbs getting a lower value.

  For fly ash mixes, both the 7 and 91-day values of charge passed were similar to their respective binary binder mixes. Hence as with the binary binder mixes, the ternary binder mixes with up to 60% fly ash replacement all had lower values of charge passed compared to the control mix with the mix with 80% replacement having a significantly higher value.

- Unlike the sorptivity test, curing had a positive effect on the charge passed with the values reducing with age however the results do not seem to have a correlation with the concrete compressive strength.

4. Overall conclusion

- For the durability test results, the replacement levels (binary binder) of ggbs and fly ash for which mixes had a similar or better performance was 40% or higher and up to 40% respectively. Now also taking into consideration the compressive strength results, the optimum replacement levels of ggbs and fly ash for which the mix had similar or superior performance overall (both categories) is 40 and 20% respectively.

- There is great potential for the use of ternary binder mixes. For instance considering the ternary binder mix with 80% ggbs which only had 16% Portland cement attained strength of about 42 MPa at 28 days (50 MPa at 91 days) which is sufficient for many structural purposes. Furthermore, its durability performance, even with the lower relative strength, was better than both the control mix and its respective binary binder mix.

- Similarly with fly ash mixes, the ternary binder mix with 40% replacement which contains only 48% Portland cement attained a strength of 42MPa at 28 days (51MPa at 91 days) having similar durability performance as its respective binary binder mix. The ternary binder mix with 80% fly ash, attaining strength of 7 and 10 MPa at 28 and 91 days respectively, could be a practical option for applications with low-strength requirements however unlike ggbs its durability performance was inferior to both the binary binder and the control mix.

Chapter 8 Flowing and Underwater Concrete Results

In this chapter, the test results of the other two types of high-consistence concrete i.e. flowing concrete and underwater concrete, with binary and ternary blended binders are presented and discussed. Having analysed the SCC test results, it was concluded that the optimum replacement levels of ggbs and fly ash, considering both the strength and durability performance, was 40 and 20% respectively (Chapter 7). The overall performance of these SCC mixes, with both binary and ternary blended binders, was similar to and in most cases better than the control mix. It was decided to perform tests on flowing and underwater concrete mixes containing only these optimum replacement levels of ggbs and fly ash, with both binary and ternary blended binder, in addition to the control mix and the binary binder with 20% limestone powder replacement, reducing the total number of mixes from 20 (as for SCC) to 6 for each of the two types of concrete. Hence it is possible to compare the effects of these binder compositions on these two other types of high-consistence concrete to those on SCC.

8.1 Flowing concrete

In this section the results of tests on flowing concrete (FC) with the different binder compositions are presented and discussed. As with the SCC mixes, a control mix was initially designed and produced (Table 6-4) and then the required portion of the Portland cement was replaced with the various additions (by volume) producing the binary and ternary binder mixes. The SP dosages were adjusted, if necessary, to ensure all mixes achieved the target fresh property i.e. slump of 220±20mm. The fresh properties of the mixes are given in Table 8-1 with the full mix proportions given in the Appendix 5. All the mixes achieved the target slump with the flow table results ranging between 500-550mm (Class F4). As for the rheology, the yield stress and plastic viscosity values were less variable compared to those for SCC mixes which could be due to the fact that a greater number of SCC mixes were tested and that the range of SCC slump flow values are on the upper-end of the scale resulting in larger fluctuations in these rheological parameters. Comparing these values to those for SCC, for the same plastic viscosity range, FC mixes has higher yield stress values which is expected as it has a relatively lower consistence. Further discussion is given in Chapter 9. As with SCC, the hardened properties of FC mixes were then measured at ages up to 91 days.

Table 8-1 Fresh properties of FC mixes

Mix No.	Mix Ref.	Slump	Slump flow	Flow table	Two-point test	
					Yield Stress	Plastic Viscosity
		(mm)	(mm)	(mm)	(Pa)	(Pas)
21	FC-C	240	470	545	159	21.6
22	FC-L20	230	460	540	149	17.6
23	FC-G40	240	420	510	239	17.8
24	FC-F20	240	460	535	143	18.2
25	FC-TB-G40	230	440	510	141	22.4
26	FC-TB-F20	235	420	530	115	18.1

As the SP dosage had to be adjusted for each mix, it is not possible to separate the effects of the additions on the fresh properties of FC from the above results. As with the SCC mixes, indirect indication can be attained from the SP dosages required and, as expected, the SP dosage reduced with the inclusion of additions. For instance, the SP dosage for the control mix was 0.5% by weight of binder whereas for the binary binder mixes with limestone powder, ggbs and fly ash, to achieve a similar consistence, the dosage was reduced to 0.3, 0.2 and 0.1% respectively. This indicates that the inclusion of the additions, as observed in SCC mixes, leads to an increased consistence i.e. higher slump value.

8.1.1 Effect of additions on hardened mechanical properties of flowing concrete

In this section, the results of the cube compressive and tensile splitting tests and the results of the two non-destructive tests i.e. ultrasonic pulse velocity and dynamic elastic modulus tests are given and discussed. The results (average of three measurements) of the cube compressive and tensile splitting tests are given in Table 8-2 and Table 8-3 respectively with the full data set given in Appendix 6.

8.1.1.1 Compressive strength

8.1.1.1.1 Binary binder mixes

From Table 8-2, it can be seen that, as with SCC mixes, the binary binder mixes with ggbs, fly ash and limestone powder all had lower early-age strength (up to 7 days) compared to the control mix. However their long-term (91-day) strengths were also lower than that of the control mix; 59.9, 47.9 and 53.6 MPa respectively compared to 65.9 MPa, whereas the corresponding SCC ggbs and fly ash mixes (SCC-G40 and SCC-F20 respectively) both achieved similar or higher compressive strength than the control mix SCC-C. As for the mix with limestone powder replacement (FC-L20), the compressive strength at 91 days was almost 20% lower than the control mix whereas with SCC it was only 6% lower. This could be attributed to the lower water/cement ratio of SCC where the negative effect of utilising limestone powder i.e. reduction in long-term strength is less profound as at such low water/cement ratios (<0.36) the cement is unable to undergo complete hydration due to insufficient availability of water-filled space, hence some proportion of the cement powder actually acts as an inert filler which can be substituted without sacrificing performance (Powers, 1949; Powers, 1958). This is not so much the case with water/cement ratio 0.44 as, according to Powers' model, for water/cement ratios of 0.42 or higher there will be sufficient space available for full hydration of cement paste. Although the mixes were unable to attain strengths as high as the control mix, the positive effects of curing can be seen with the strengths increasing with age of specimen.

Table 8-2 Cube compressive strength of FC mixes

			Compressive strength (MPa)					
Binder	**Mix no./Age (days)**		**1**	**3**	**7**	**28**	**56**	**91**
Control (PC)	21	0%	23.1	40.1	47.5	55.9	62.1	65.9
Limestone	22	20%	15.0	29.6	38.4	46.6	50.6	53.6
GGBS	23	40%	9.6	24.1	36.0	51.4	56.1	59.9
Fly Ash	24	20%	9.5	21.5	28.2	38.3	43.9	47.9
Ternary Binder-GGBS	25	40%	7.3	18.4	27.3	42.7	48.4	50.4
Ternary Binder-Fly Ash	26	20%	8.0	18.5	25.4	34.5	39.8	44.1

Looking at Figure 8-1, it can be seen that there is a higher rate of strength development for the 40% ggbs mix (FC-G40) between 7 and 28 days compared to that of the control mix however at later ages the strength development seems to be similar to the control mix with the magnitude still lower. For the fly ash and limestone powder mixes, unlike ggbs, the strength development rates seem to be similar, with the strength values lower at all ages, compared to the control mix. Considering the strength development trend for the three binary binder mixes it would seem that the probability of either of them attaining similar strengths as the control mix, even at much later ages, is low.

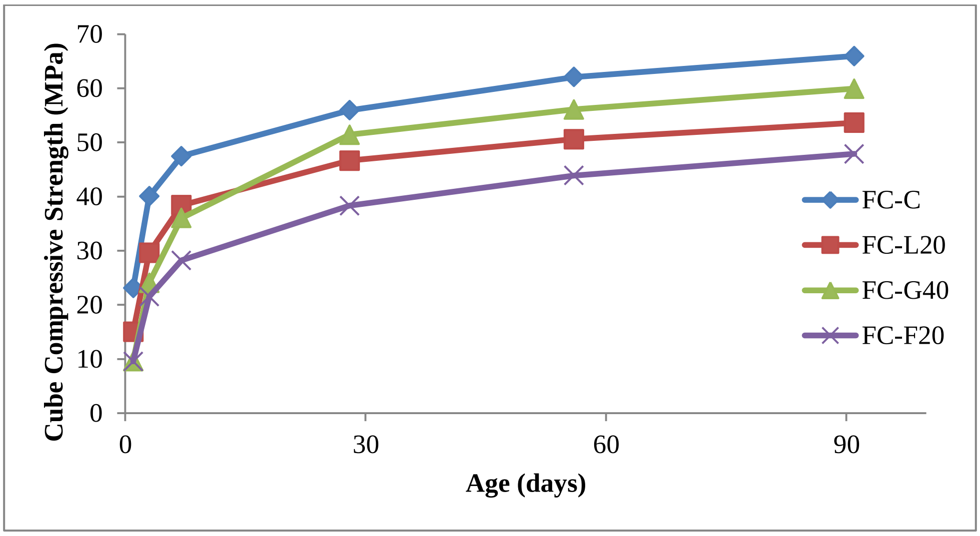


Figure 8-1 Effect of different additions on the strength development of FC mixes (binary binder)

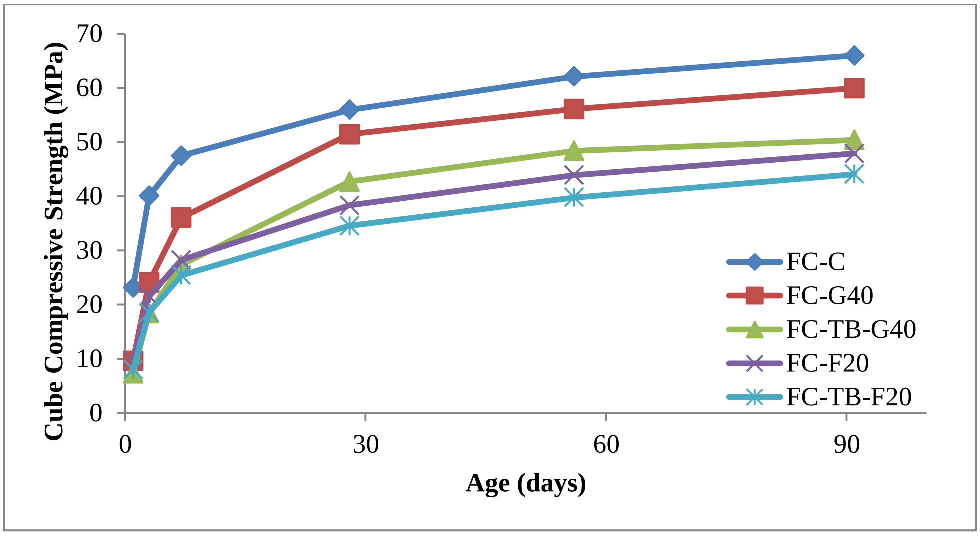


Figure 8-2 Comparison of strength development of binary and ternary binder FC mixes with ggbs and fly ash

8.1.1.1.2 Ternary binder mixes

The ternary binder mixes, FC-TB-G40 and FC-TB-F20 with 40% ggbs and 20% fly ash respectively, both had a lower compressive strength at all ages up to 91 days compared to their corresponding binary binder mixes (FC-G40 and FC-F20 respectively) (Table 8-2). Figure 8-2 shows the strength development rate for the binary and ternary binder mixes with ggbs seem to be similar to the strength of FC-TB-G40 mix and was 8-10 MPa lower than that of FC-G40 mix at all ages. Also the strength development rate, between 56 and 91 days, of FC-TB-G40 seems to be less than that for FC-G40; this is reflected by the fact that the ternary binder mix at 56 days attained 86% of the binary binder mix strength whereas at 91 days this was reduced to 84% due to reduction in rate of strength development. Hence from this trend it seems unlikely that the compressive strength of the ternary binder mix will ever reach that of the binary binder mix.

As with the ggbs mix, the ternary binder mix with fly ash, FC-TB-F20, had a similar strength development rate to the corresponding binary binder mix, FC-F20, though in this case the strength magnitude of FC-TB-F20 was only about 2-4 MPa lower than that of FC-F20 at all ages. The ternary binder mix attained 90, 91 and 92% of the binary binder mix strength at 28, 56 and 91 days respectively, indicating that its strength development rate is slightly higher than that of FC-F20; assuming a similar trend was to continue then there would be a possibility for the ternary binder mix to attain similar strength to the binary binder mix at a later age though it is doubtful that this rate would be able to sustain itself for that period of time hence the most likely case is that, as with ggbs, the ternary binder mix would not be able to attain similar strengths to the binary binder mix.

These trends are different to that observed with SCC mixes where, as mentioned, both the 91-day strength of the ternary binder mixes were higher than their corresponding binary binder mixes; also there does not seem to be any noticeable change in the rate of strength development between the binary and ternary binder mixes. So in this case the use of ternary blended binders resulted in lower early-age and long-term compressive strength, hence unlike the SCC mixes, no synergistic effect was noticed between the limestone powder and ggbs and fly ash.

8.1.1.2 Tensile splitting strength

The tensile splitting strength also increased with age of concrete (Table 8-3) reflecting the positive effects of curing. The relationship between the cube compressive and the tensile splitting strength of the mixes, as with the SCC mixes, fell well within the typical ranges given by both BS EN 1992-1-1 (2004) and CEB-FIB Model 90 (1993), and was independent of both the powder combination and the testing age (Figure 8-3). Referring to Table 8-3, we can see that the ratios between the compressive and the tensile splitting strength range between minimum of 6.5% for the control mix at 91 days to maximum of 10.1% for ternary binder mix with fly ash at 28 days, with majority fall in the 7-8% range. The average ratio at 28 and 91-day was 8.3 and 7.8% respectively giving an overall average of about 8% which falls, as with that for SCC mixes, within the typical range of 8-10% suggested by Neville (2011).

Table 8-3 Tensile splitting strength of FC mixes

			Tensile splitting strength (MPa)		Tensile splitting strength/Compressive strength ratio (%)	
Binder	**Mix no./Age (days)**		**28**	**91**	**28**	**91**
Control (PC)	21	0%	4.0	4.3	7.2	6.5
Limestone	22	20%	3.8	4.2	8.1	7.7
GGBS	23	40%	4.0	4.4	7.8	7.3
Fly Ash	24	20%	3.1	3.9	8.1	8.1
Ternary Binder-GGBS	25	40%	3.6	4.2	8.4	8.3
Ternary Binder-Fly Ash	26	20%	3.5	3.9	10.1	8.9

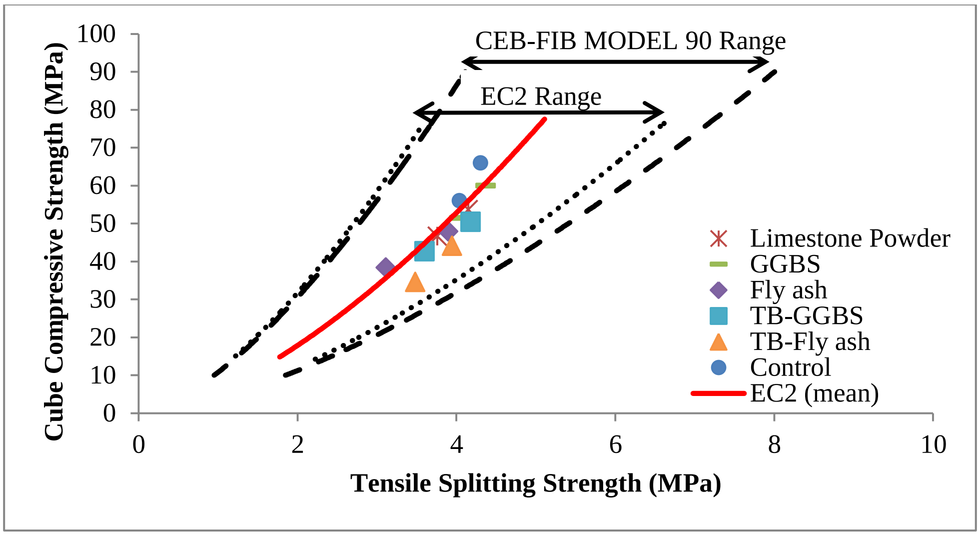
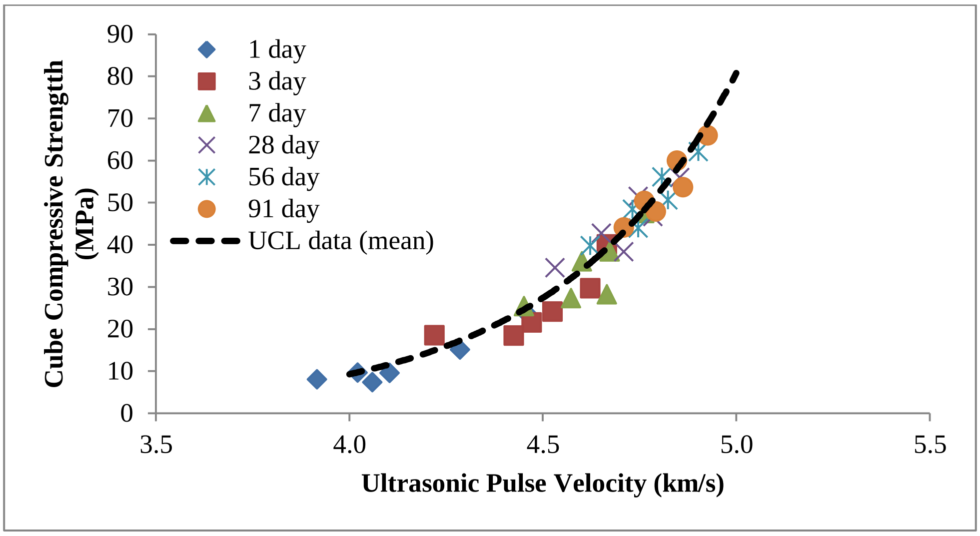


Figure 8-3 Comparison of compressive strength vs. tensile splitting strength of FC mixes with relationships from EC2 and CEB-FIB Model 90

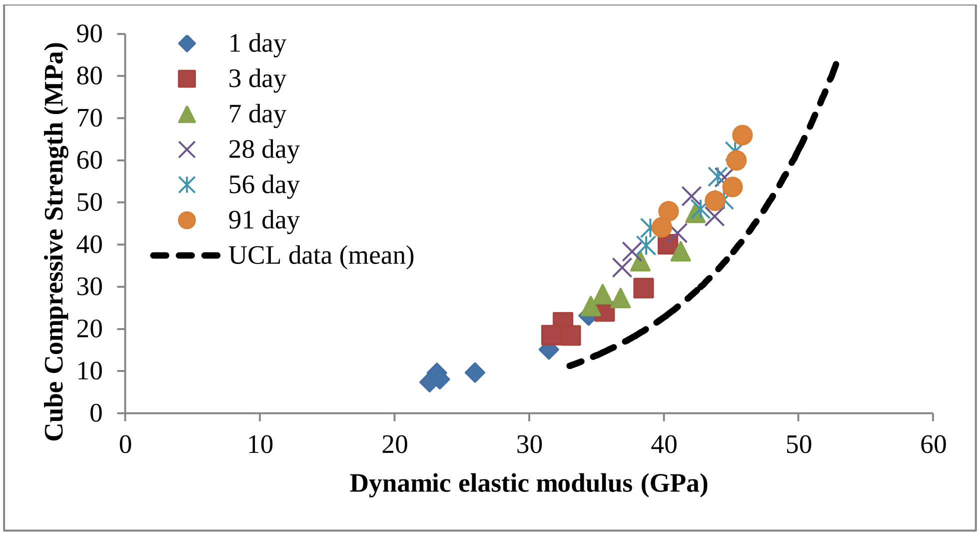
8.1.1.3 Non-destructive tests

The results of the non-destructive tests displayed similar trends to the compressive strength, increasing with age of the specimen; the tabulated results are given in Appendix 6. The UPV results, illustrated in Figure 8-4 (a), show a clear correlation with the compressive strength, independent of the powder composition and testing age. The results, as with those obtained for SCC mixes, fit well with the relationship obtained at UCL for normal-consistence concrete with similar aggregate types (Domone & Illston, 2010).

The dynamic elastic modulus results also showed a clear correlation with the compressive strength results independent of the powder composition and testing age (Figure 8-4 (b)). As with the SCC results, the results are, for a given compressive strength, consistently lower (by about 5 GPa) compared to those previously obtained at UCL. This difference was initially attributed to the lower coarse aggregate content of SCC (around 35% by volume) compared to that of normal-consistence concrete (around 45% by volume) (7.2.3) however in this case, this trend is observed even though the coarse aggregate content of FC was similar to that of normal-consistence concrete at 42%. As mentioned previously, the control mix was initially designed using the BRE mix design method as a normal-consistence concrete with a slump of 75mm with the higher slump achieved with use of superplasticisers (6.2), hence it was expected that the dynamic elastic modulus results follow that of normal-consistence concrete.



(a)



(b)

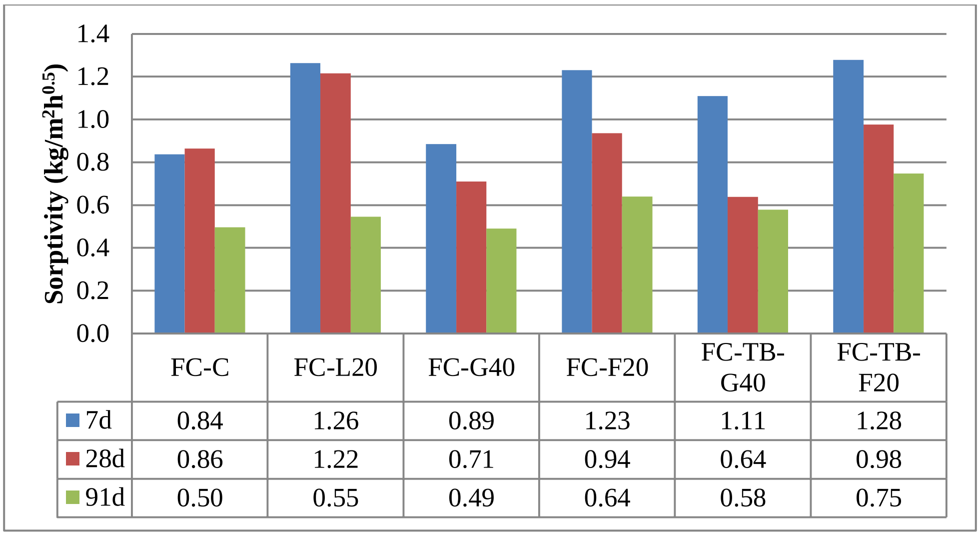
Figure 8-4 Relationship between Compressive strength and (a) UPV and (b) dynamic elastic modulus results of FC mixes

8.1.2 Effect of additions on durability properties of flowing concrete

As with SCC mixes, the sorptivity and the rapid chloride penetration tests were also performed on FC mixes. In this section the results of these tests are given and discussed. The full set of results is given in Appendix 6 and Appendix 8 respectively.

8.1.2.1 Sorptivity

As with the SCC, the water intake over the first four hour period of immersion was proportional to the square root of time irrespective of the powder combination and testing age. The sorptivity coefficient results are illustrated in Figure 8-5. As it can be seen, unlike the SCC results, here there is a clear trend of reduction in sorptivity coefficient with increase in age of specimen, as expected, which reflects the positive effects of curing.



	FC-C	FC-L20	FC-G40	FC-F20	FC-TB-G40	FC-TB-F20
🟦 7d	0.84	1.26	0.89	1.23	1.11	1.28
🟥 28d	0.86	1.22	0.71	0.94	0.64	0.98
🟩 91d	0.50	0.55	0.49	0.64	0.58	0.75

Figure 8-5 Sorptivity coefficient (short-term) of FC mixes with different binder compositions

8.1.2.1.1 Binary binder mixes

The binary binder mix with limestone powder (FC-L20), as with SCC-L20, had a higher 7 and 28-day sorptivity results whereas at 91 days it attained a coefficient similar to that of the control mix. As with the SCC mixes, the binary binder mix with limestone powder had the greatest reduction in sorptivity coefficient from 7 to 91 days compared to other binary binder mixes albeit the sorptivity values were slightly lower for FC-L20 (1.26 and 0.55 kg/m^{2}h$^{0.5}$ respectively) than SCC-L20 (1.42 and 0.62 kg/m^{2}h$^{0.5}$ respectively).

The mix with ggbs (FC-G40) attained a similar sorptivity coefficient at 7 and 91 days (0.89 and 0.49 kg/m^{2}h$^{0.5}$ respectively) to the control mix (0.84 and 0.50 kg/m^{2}h$^{0.5}$ respectively). This was also the case for SCC-G40; however unlike the SCC here the change in sorptivity coefficient from 7 to 91 days is greater with a maximum difference of 0.4 compared to 0.1 kg/m^{2}h$^{0.5}$ for the SCC. In general the sorptivity coefficients for FC were higher than those for SCC at 7 and 28 days. This could be attributed to the lower water/cement ratio of SCC with the hydration products forming a denser matrix.

Fly ash mix (FC-F20) had a slightly higher sorptivity coefficient at all ages compared to the control mix, contradictory to the SCC mix (SCC-F20) which gave a lower 7 and 91-day sorptivity coefficient compared to the corresponding control mix. The sorptivity coefficients for FC-F20, as with FC-G40, were higher than those for SCC-F20 which could again be attributed to the lower water/cement ratio of SCC and also here the change in sorptivity from 7 to 91 days is greater compared to that in SCC-F20; maximum difference of 0.59 compared to 0.28 kg/m^{2}h$^{0.5}$ respectively. Looking at Figure 8-5, it can be noticed that both FC-F20 and FC-G40 have a similar reducing trend with the coefficients for the fly mix consistently higher (by 0.25 kg/m^{2}h$^{0.5}$ on average) than the ggbs mix.

8.1.2.1.2 Ternary binder mixes

The ternary binder mix with ggbs (FC-TB-G40) had a higher 7 and 91-day sorptivity coefficient than the corresponding binary binder mix (FC-G40) although the 28-day coefficient was lower than both the binary mix and the control mix; 0.64 compared to 0.71 and 0.86 kg/m^{2}h$^{0.5}$ respectively (Figure 8-5), hence no synergistic effects were noticed due to the presence of limestone powder. The early-age sorptivity coefficient was also higher in SCC-TB-G40 however unlike FC the 91-day coefficient was lower than both the binary binder and the control mix. This could be attributed to both the lower water/cement ratio of SCC and the synergistic effects of limestone powder which, as mentioned, appears to be greater at lower water/cement ratios. The incorporation of limestone powder only resulted in greater change in sorptivity coefficient compared to the corresponding binary binder mix; 0.53 compared to 0.4 kg/m^{2}h$^{0.5}$, however this is not so much an advantage because, as mentioned, the individual magnitudes were higher than that of FC-G40.

Ternary binder fly ash mix (FC-TB-F20) gave a higher sorptivity coefficient at all ages compared to both its corresponding binary binder mix (FC-F20) and control mix, hence, as with ggbs mixes, no synergistic effect could be noticed due to the presence of limestone powder. The ternary binder SCC mix (SCC-TB-F20) with fly ash also had a higher 7-day sorptivity coefficient than the binary binder mix (SCC-F20) however, unlike FC-TB-F20 its 91-day sorptivity coefficient was similar to both that of the corresponding control mix and binary binder mix. Hence, as with the ggbs mixes, the inclusion of limestone powder did not have any positive effects and instead increased the sorptivity coefficients at all ages.

As expected a similar trend, as that found with SCC mixes, exists between the sorptivity coefficient and the cube compressive strength of FC mixes (Figure 8-6). The degree of scatter is higher in this case; R^2 of 0.615 compared to 0.713 for SCC though this could be due to the lower number of data points for FC mixes due to lower number of mixes.

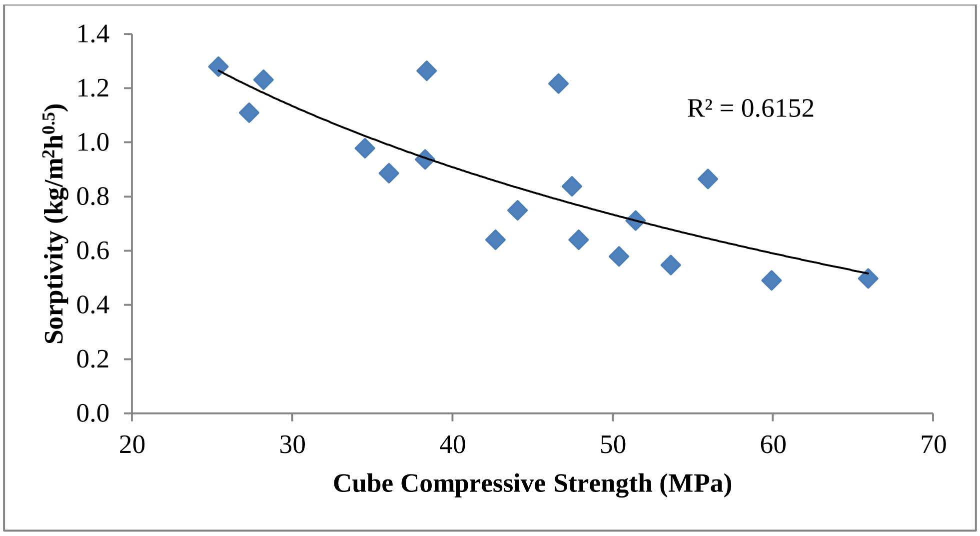


Figure 8-6 Relationship between sorptivity coefficient (short-term) and the cube compressive strength of FC mixes

8.1.2.2 Rapid chloride penetration test

As with the sorptivity coefficient results, curing has a positive effect on the rapid chloride penetration test results; the total charge passed values reduces with increase in age of concrete for all mixes. The results are given in Table 8-4 and illustrated in Figure 8-7.

8.1.2.2.1 Binary binder mixes

The binary binder mix with 20% limestone powder (FC-L20) had a lower value of charge passed at 7 days (4106 Coulombs) than the control mix (6645 Coulombs) however it had higher values at 28 and 91 days; 3905 and 2655 Coulombs compared to 2700 and 1980 Coulombs respectively. As mentioned, the repeatability of this test is about 34% hence taking this into account, the difference between the values of the control mix and FC-L20 is not large enough for them to be significantly different. Comparing with the corresponding SCC mix (SCC-L20), the FC mix gave lower values of charge passed (reduction of 50% or greater) at all ages, though still the 91-day value of charge passed is high achieving a rating of “Moderate” according to ASTM C1202 (2007).

Lower values of charge passed were obtained for FC mix with ggbs (FC-G40) compared to the control mix at all ages. For SCC mix with 40% ggbs, a similar 7-day value was obtained but, as with FC mix, lower values were obtained at 28 and 91 days than their corresponding control mix. Both achieved a rating of “Very Low” at 91 days. There is a big drop in value of charge passed from 7 to 28 days with a relatively smaller difference between the 28 and 91-day values. This could be attributed to the secondary reaction between the $Ca(OH)_2$ and ggbs forming cementitious compounds.

The fly ash mix, FC-F20 had a similar 7 and 28-day values of charge passed compared to the control mix. However the long-term (91-day) value of charge passed was lower than the control mix; 1000 compared to 1980 Coulombs respectively. A similar trend was observed with SCC mixes. Both SCC and FC mixes achieved excellent ratings of “Very Low” and “Low” respectively at 91 days with the FC mix bordering on “Very Low” rating. Referring to Figure 8-7, it can be seen that, unlike the ggbs mix, there is a greater decrease in the charge passed between 28 and 91 days than from 7 to 28 days. This difference could be attributed to the chemical nature of these two additions, ggbs being a hydraulic material reacts quicker than fly ash which is a pozzolan.

Table 8-4 Rapid chloride penetration test results for FC mixes

			Total charge passed (Coulombs)			**Rating according to ASTM C1202** (2007)		
Binder	**Mix no./Age (days)**		**7**	**28**	**91**	**7**	**28**	**91**
Control (PC)	21	0%	6645	2700	1980	High	Moderate	Low
Limestone	22	20%	4106	3905	2655	High	Moderate	Moderate
GGBS	23	40%	2596	1175	900	Moderate	Low	Very Low
Fly Ash	24	20%	5956	4180	1000	High	High	Low
Ternary Binder-GGBS	25	40%	1330	1188	508	Low	Low	Very Low
Ternary Binder- Fly Ash	26	20%	2700	1589	480	Moderate	Low	Very Low

8.1.2.2.2 Ternary binder mixes

The ternary blended binder mixes FC-TB-G40 and FC-TB-F20 both had similar or lower values of charge passed at all ages compared to their corresponding binary binder mixes. Looking at the ratings given in Table 8-4, it can be seen that the binary binder mixes with ggbs and fly ash had a 7-day rating of “Moderate” and “High” respectively whereas with the inclusion of limestone powder, the ratings improved to “Low” and “Moderate” respectively. A similar trend was seen with SCC mixes where the ternary binder mixes achieved similar or lower values of charge passed compared to their corresponding binary binder mix. This is an advantage as concrete with similar performance can be obtained with a higher Portland cement replacement which reduces both the cost and carbon footprint of concrete. This is further discussed in Chapter 9.

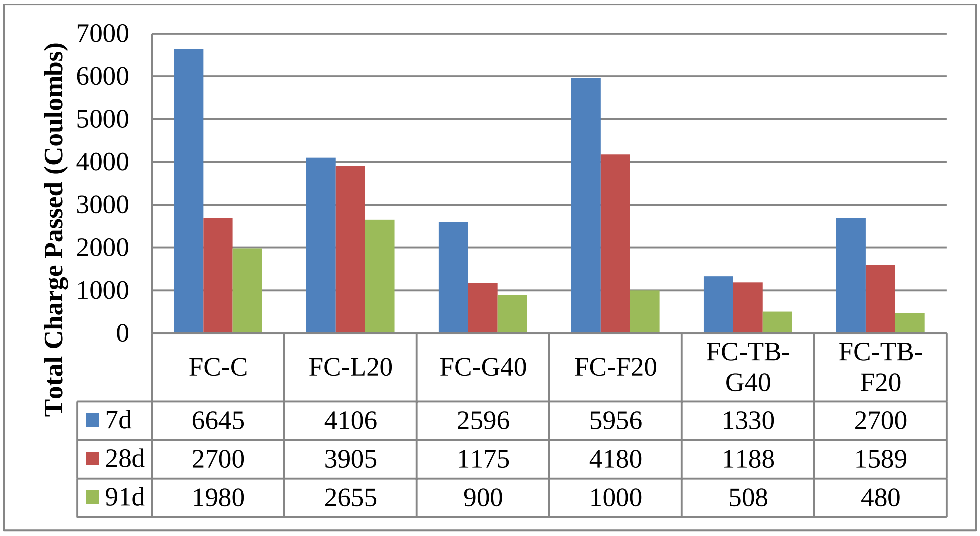


Figure 8-7 Total charge passed of FC mixes with different binder compositions

Unlike the sorptivity results, no correlation was noticed between the values of total charge passed and the cube compressive strength of the mixes (Figure 8-8). This was also mirrored by the SCC results (Figure 7-18).

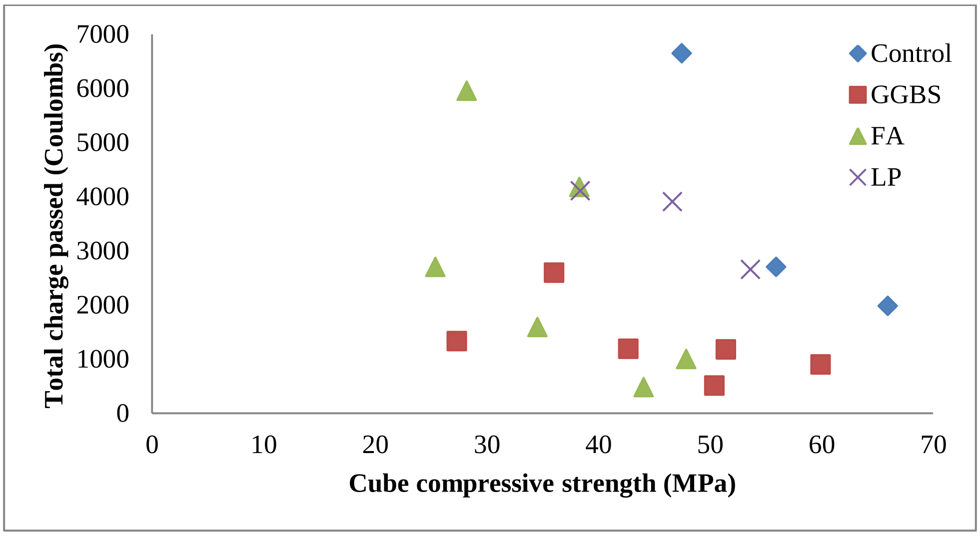


Figure 8-8 Relationship between the RCP test results and cube compressive strength for FC mixes

8.2 Underwater concrete

In this section the results of tests on underwater concrete (UWC) with the different binder compositions are presented and discussed. As with FC, initially the UWC control mix with solely Portland cement was designed and produced (Table 6-5) and then subsequently the binary and ternary binder mixes were produced by replacing a portion of the cement (by volume) with the required addition. For all mixes, both the SP and AWA dosages had to be adjusted to ensure the target fresh properties were achieved i.e. slump of 220±20mm and washout of less than 15%. For example, the control mix had SP and AWA dosage of 0.7 and 0.5% by weight of binder respectively whereas for the binary binder mix with 20% fly ash (UWC-F20) the SP dosage had to be reduced to 0.5% and the AWA dosage increased to 0.7%. The fresh properties of the mixes are given in Table 8-5 with the full set of mix proportions given in the Appendix 5. All the mixes achieved the target slump and washout with the flow table results ranging between 415 - 455mm (Class F3). The yield stress and plastic viscosity values were higher compared to SCC mixes, which could be attributed to the lower slump value of UWC. However these values are also higher than those for FC mixes which had a similar slump values to UWC; this can be attributed to the ‘sticky’ nature of the mix due to the addition of AWA. This is further discussed in Chapter 9. As with SCC and FC, the hardened properties of UWC mixes were then measured at ages up to 91 days with the exception of the 1-day test.

Table 8-5 Fresh properties of UWC mixes

Mix No.	Mix Ref.	Slump	Slump flow	Flow table	Washout Test	Two-point test	
						Yield Stress	Plastic Viscosity
		(mm)	(mm)	(mm)	(%)	(Pa)	(Pas)
27	UWC-C	215	390	415	9	501	54.6
28	UWC-L20	235	415	455	13	246	48.8
29	UWC-G40	230	420	450	14	265	36.1
30	UWC-F20	220	400	415	7	468	72.2
31	UWC-TB-G40	230	400	420	10	392	54.1
32	UWC-TB-F20	240	440	460	14	397	34.5

8.2.1 Effect of additions on hardened mechanical properties of underwater concrete

In this part the results of the cube compressive and tensile splitting tests and the two non-destructive tests are given and discussed. The results of the cube compressive and tensile splitting tests are given in Table 8-6 and Table 8-7 respectively.

8.2.1.1 Compressive strength

8.2.1.1.1 Binary binder mixes

As with SCC and FC mixes, the early age strength (up to 7 days) of UWC mixes incorporating limestone powder, ggbs and fly ash replacement are lower than the control mix (UWC-C) (Table 8-6). As with FC mixes, they also had lower 91-day strength compared to the control mix; 47.2, 56.4 and 59.2 MPa respectively compared to 65.6 MPa, however unlike FC mixes, the strength of the fly ash mix (UWC-F20) was consistently higher than the ggbs mix (UWC-G40).

Table 8-6 Cube compressive strength of UWC mixes

			Compressive strength (MPa)						
			Air cast					**Tremie cast**	
Binder	**Mix no./Age (days)**		**3**	**7**	**28**	**56**	**91**	**28**	**91**
Control (PC)	27	0%	41.7	52.7	61.2	63.4	65.6	52.7	61.9
Limestone	28	20%	28.1	35.0	41.9	45.9	47.2	35.5	41.6
GGBS	29	40%	21.5	33.6	44.2	50.4	56.4	37.9	47.0
Fly Ash	30	20%	32.2	38.5	47.6	54.1	59.2	38.7	48.0
Ternary Binder-GGBS	31	40%	18.5	29.1	46.2	50.5	53.9	37.0	43.3
Ternary Binder-Fly Ash	32	20%	20.3	25.2	32.4	41.0	45.5	29.9	39.5

Referring to Figure 8-9, it can be seen that, as with SCC and FC mixes, the compressive strength increases as the concrete matures reflecting the positive effects of curing. The strength development rate of all the mixes were similar up to

28 days, and thereafter the mix with limestone powder had a similar rate to the control mix (UWC-C) up to 91 days with the strength values being consistently about 18-20 MPa lower. The strength development rate of the ggbs and fly ash mix were similar up to 91 days and higher than that of the control mix; the fly ash mix attained almost 78% of the control mix strength at 28 days, a reduction of 22%, whereas at 91 days the reduction in strength was only 10%, hence, unlike the FC mixes and the mix UWC-L20, here there is good chance for the ggbs and fly ash mixes in attaining a similar or even surpassing the strength of the control mix at a later age.

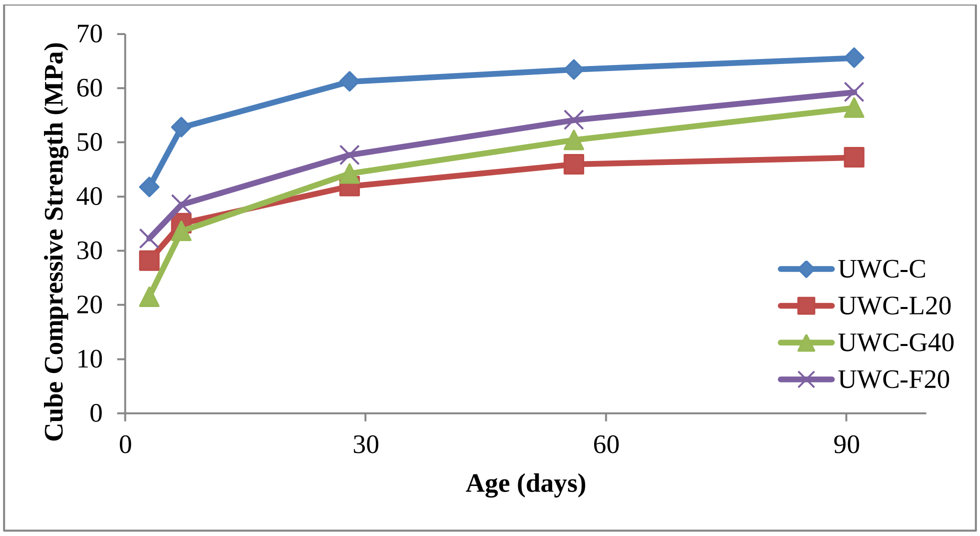


Figure 8-9 Effect of different additions on the strength development of UWC mixes (binary binder)

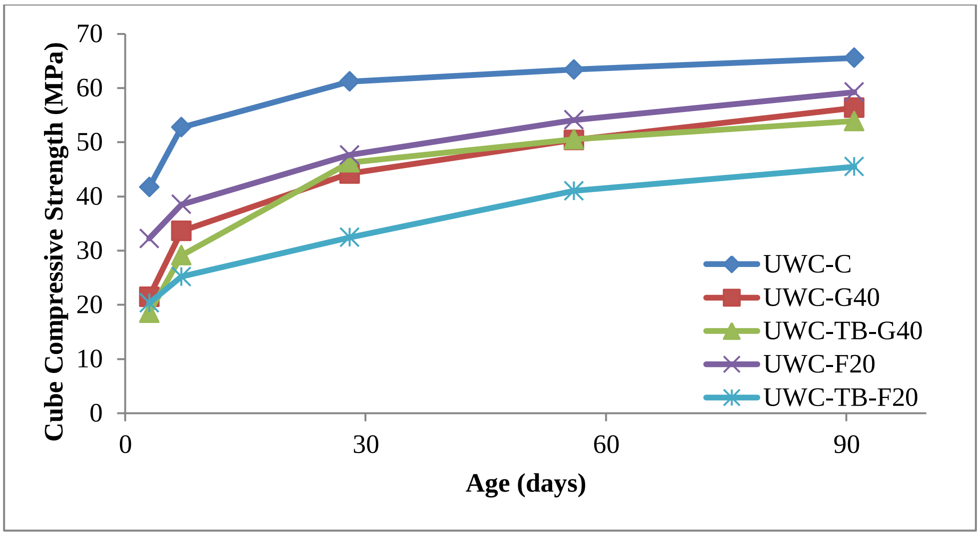


Figure 8-10 Comparison of strength development of binary and ternary binder UWC mixes with ggbs and fly ash

8.2.1.1.2 Ternary binder mixes

As with the FC mixes, the ternary binder mixes, UWC-TB-G40 and UWC-TB-F20 had a lower 7 and 91-day strength compared to their corresponding binary binder mix. The mix UWC-TB-F20 had a consistently lower strength (about 13-15 MPa) compared to the binary binder mix UWC-F20 (Figure 8-10). The ternary binder mix attained 65% of the strength of binary binder mix at 7 days whereas at 91 days it had attained 77% of the strength, indicating that the strength development rate of the ternary binder, as with the FC mix FC-TB-F20, is slightly higher than the binary binder however it is doubtful, given the magnitude difference, that the ternary binder mix will ever attain the same strength as the binary binder mix at a later age.

The ternary binder mix with ggbs (UWC-TB-G40) on the other hand had a much lower reduction in strength of 13 and 4% compared to its binary binder mix (UWC-G40) at 7 and 91 days respectively. Referring to Figure 8-10, the ternary binder mix attained similar strengths as the binary binder mix at 28 and 56 days, however its strength development rate was lower compared to that of the binary binder mix after 56 days resulting in the 4% reduction in strength at 91 days. Given that the 91-day strength reduction is very small, depending on the strength development rate of the binary binder mix, there is a possibility that UWC-TB-G40 can attain similar strength as UWC-G40 at a later age. A similar trend was observed with FC mixes where the strength development rate of the ternary binder mix with ggbs was lower compared to the binary binder mix between 56 and 91 days (Figure 8-2).

8.2.1.1.3 Tremie cast specimens

As mentioned in 4.4.1, for the UWC mixes, in addition to the cubes cast in air, 6 cubes were also cast underwater using the tremie method as an attempt to mirror in-situ practice. The compressive strength of these cubes was measured at ages of 28 and 91 days (3 cubes per age) and the results are given in Table 8-6. According to the literature, the compressive strength of concrete cast underwater (e.g. tremie cast) should be at least 80% of that cast in dry conditions (air cast) (Assaad et al., 2011; Sonebi & Khayat, 2003).

Looking at Figure 8-11, it can be noticed that there is a good linear relationship (R^2=0.917) between the compressive strengths of the specimens cast in air and those using the tremie method. All the tremie cast cubes attained a compressive strength ratio of 80% or higher relative to the respective air cast cubes, with the lowest and highest being 80 and 94% for the 91-day strength of UWC-TB-G40 and the control mix (UWC-C) respectively.

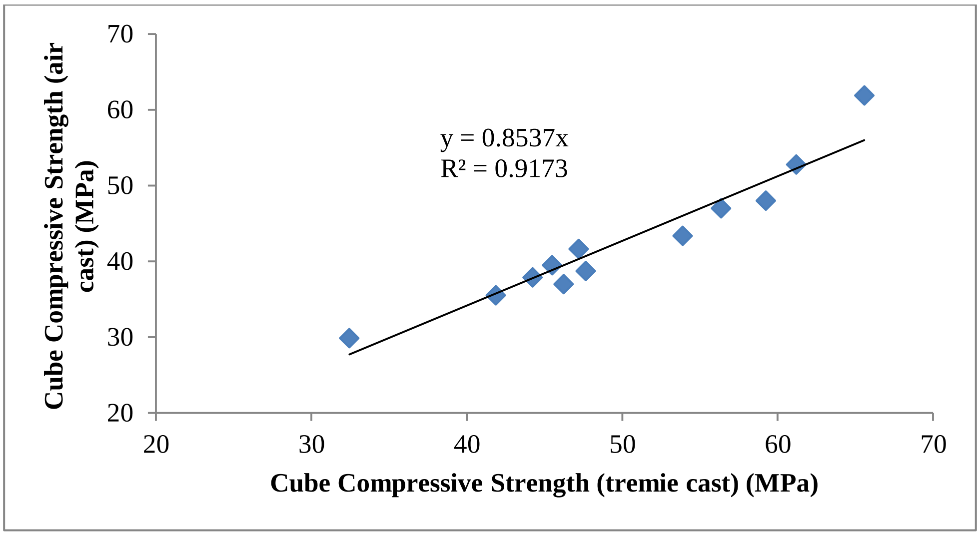


Figure 8-11 Relationship between compressive strength of specimens cast in air with those using the tremie method

8.2.1.2 Tensile splitting strength

Curing had a positive effect on the tensile splitting strength; higher values were attained with increase in age (Table 8-7). As with both SCC and FC, the relationship between the cube compressive strength and tensile splitting strength of UWC mixes fell well within the typical ranges given by the two design codes; BS EN 1992-1-1 (2004) and CEB-FIB Model 90 (1993) (Figure 8-12). The ratios between the compressive and the tensile splitting strength ranged between a minimum of 7.2% for the control mix at 28 days to maximum value of 9.4% for ternary binder mix with ggbs at 28 days, with majority falling in the 7-9% range. The average ratio at 28 and 91-day was 8.5 and 8.2% respectively giving an overall average of about 8.4% which is, as with SCC and FC mixes, within the range of 8-10% suggested by Neville (2011).

Table 8-7 Tensile splitting strength of UWC mixes

			Tensile splitting strength (MPa)		**Tensile splitting strength/Compressive strength ratio (%)**	
Binder	**Mix no./Age (days)**		**28**	**91**	**28**	**91**
Control (PC)	27	0%	4.43	5.07	7.2	7.7
Limestone	28	20%	3.28	3.78	7.8	8.0
GGBS	29	40%	4.09	4.50	9.2	8.0
Fly Ash	30	20%	3.92	4.54	8.2	7.7
Ternary Binder-GGBS	31	40%	4.37	4.97	9.4	9.2
Ternary Binder-Fly Ash	32	20%	2.93	3.92	9.0	8.6

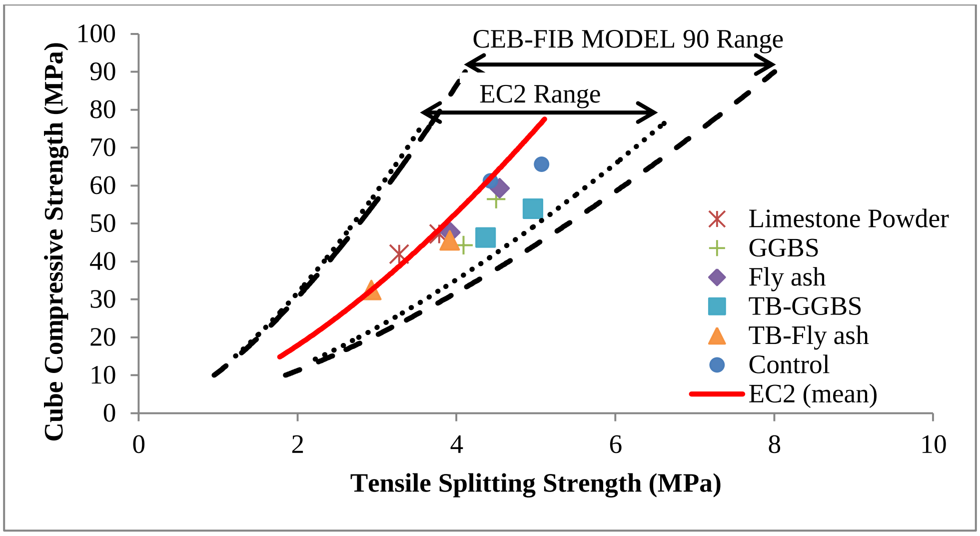
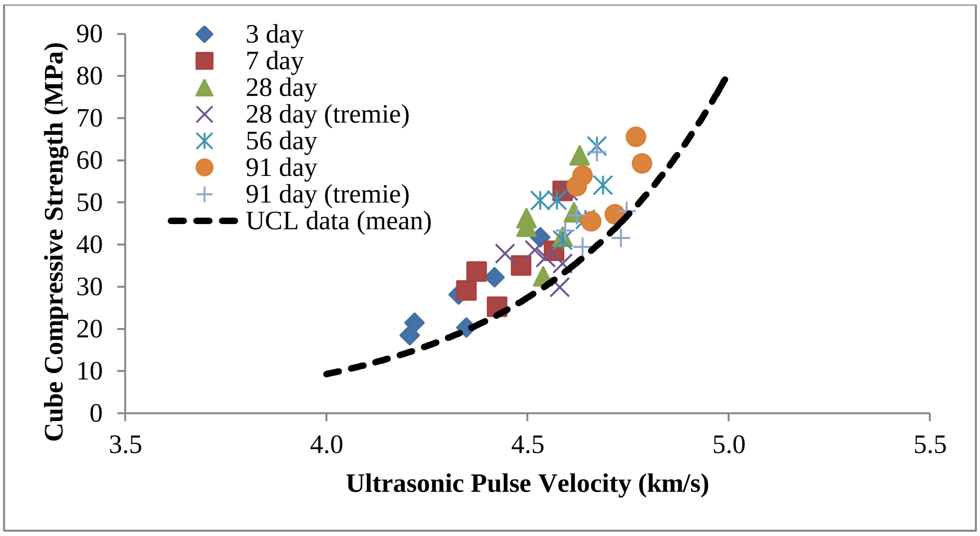


Figure 8-12 Comparison of compressive strength vs. tensile splitting strength of UWC mixes with relationships from EC2 and CEB-FIB Model 90

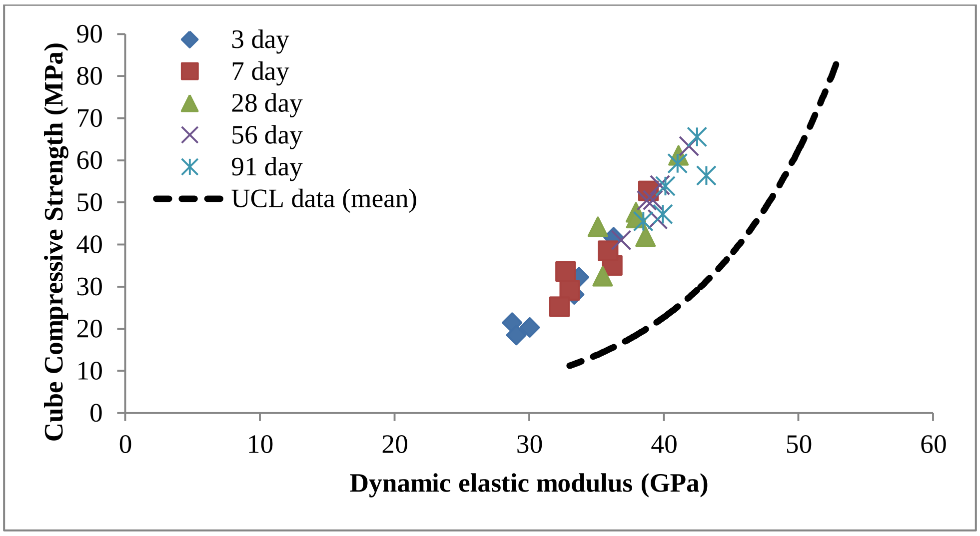
8.2.1.3 Non-destructive tests

The results of both the non-destructive tests showed a similar trend to the compressive strength results, as with both the SCC and FC results, increasing with age of the specimen. The tabulated results are given in Appendix 6. The UPV results, similar to the SCC and FC mixes, though with a slightly greater scatter, show a correlation with the compressive strength results, independent of the powder composition and testing age (Figure 8-13 (a)). Though having a similar relationship, for a given compressive strength, the UPV values are lower (by about 0.25 km/s considering the mean) than those previously obtained at UCL for normal-consistence concrete with similar aggregate types (Domone & Illston, 2010).

A clear correlation exists between dynamic elastic modulus and the compressive strength results, independent of the powder composition and testing age (Figure 8-13 (b)). As with the SCC and FC results, for a given compressive strength, the dynamic elastic modulus values are consistently lower than those previously obtained at UCL however the difference in values in this case is about 10 GPa; twice of that seen in SCC and FC mixes. The coarse aggregate content of UWC mixes are slightly lower than for the SCC mixes; 32% compared to 35% by volume, hence this could explain the lower dynamic elastic modulus compared to SCC mixes.



(a)



(b)

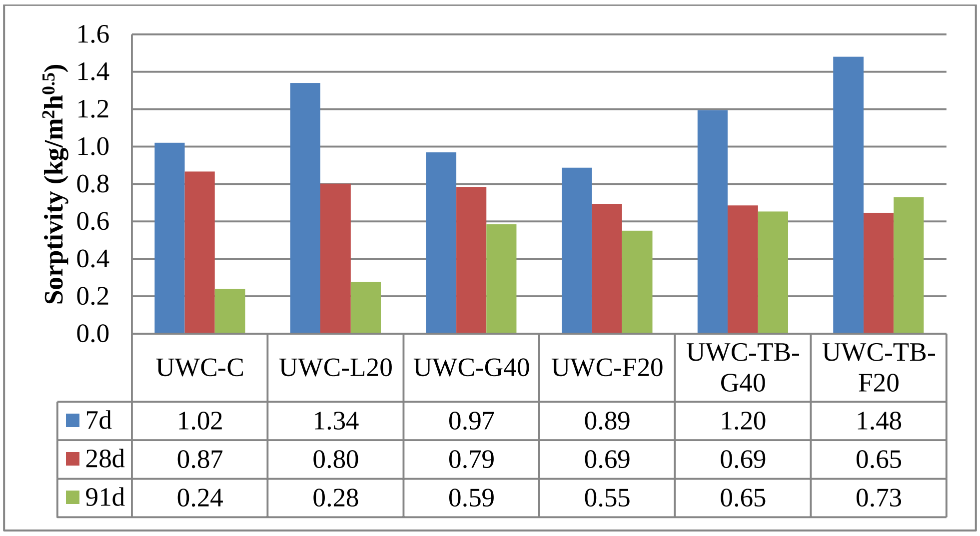
Figure 8-13 Relationship between Compressive strength and (a) UPV and (b) dynamic elastic modulus results of UWC mixes

8.2.2 Effect of additions on durability properties of underwater concrete

As with the other two types of concrete, the sorptivity and the rapid chloride penetration tests were also performed on the UWC mixes. In this section the results of these tests are presented and discussed. The full set of results is given in Appendix 6 and Appendix 8 respectively.

8.2.2.1 Sorptivity

As with SCC and FC, the water intake over the first four hour period of immersion was proportional to the square root of time irrespective of the powder combination and testing age. The sorptivity coefficient results are illustrated in Figure 8-14. As with the FC results, here also the positive effects of curing can also be noticed as there is a clear trend of reduction in sorptivity coefficient with increase in age of specimen with the exception of UWC-TB-F20 where the coefficient was slightly higher at 91-day than at 28 days.



	UWC-C	UWC-L20	UWC-G40	UWC-F20	UWC-TB-G40	UWC-TB-F20
🟦 7d	1.02	1.34	0.97	0.89	1.20	1.48
🟥 28d	0.87	0.80	0.79	0.69	0.69	0.65
🟩 91d	0.24	0.28	0.59	0.55	0.65	0.73

Figure 8-14 Sorptivity coefficient (short-term) of UWC mixes with different binder compositions

8.2.2.1.1 Binary binder mixes

As with the SCC and FC mixes, the binary binder mix with limestone powder (UWC-L20) had the greatest reduction in sorptivity coefficient from 7 to 91 days compared to other binary binder mixes; from 1.34 kg/m^{2}h$^{0.5}$ to 0.28 kg/m^{2}h$^{0.5}$ respectively and the 7-day sorptivity coefficient was higher than that of the control mix (UWC-C). Unlike both the SCC and FC mixes, in addition to the coefficient at 91 days, the 28-day value was also similar to the values obtained for UWC-C.

The mix with ggbs (UWC-G40) attained similar, albeit slightly lower, sorptivity coefficients at 7 and 28 days (0.97 and 0.79 kg/m^{2}h$^{0.5}$ respectively) compared to the control mix (1.02 and 0.87 kg/m^{2}h$^{0.5}$ respectively). However contrary to what was expected and results of SCC and FC mixes, in this case the later-age (91-day) sorptivity coefficient was higher than that of the control mix. The sorptivity coefficients of UWC-G40 are higher than that attained for both SCC and FC mixes.

The fly ash mix (UWC-F20), as with UWC-G40 mix, had a slightly lower sorptivity coefficient at 7 and 28 days and a higher 91-day coefficient compared to the control mix. The sorptivity coefficients of UWC-F20 were higher than those for the SCC-F20 mix however, unlike UWC-G40, lower than FC-F20. As with the FC mixes, referring to Figure 8-14, it can be noticed that both the fly ash mix and the ggbs mix follow a similar trend however, unlike the FC mixes, the coefficient values for the fly ash mix is actually lower, albeit slightly (by 0.08 kg/m^{2}h$^{0.5}$ on average), than those for the ggbs mix. This could be attributed to the fact that, as mentioned, the fly ash mix consistently had, unlike in FC mixes, slightly higher compressive strength (3-5 MPa) than the ggbs mix, hence the slightly lower sorptivity coefficient at all ages.

8.2.2.1.2 Ternary binder mixes

As with the FC, the ternary binder mix with ggbs (UWC-TB-G40) had a higher 7 and 91-day coefficient compared to both the binary binder mix (UWC-G40) and the control mix, however the 28-day coefficient was slightly lower than both those mixes (Figure 8-14). Hence, as with FC, here also no synergistic effects were noticed due to the presence of limestone powder, contrary to SCC mix (SCC-TB-G40) which, attributed to its lower water/cement ratio, had a lower 91-day coefficient compared to the corresponding binary binder and control mix. However, as with FC, the incorporation of limestone powder did results in greater drop in sorptivity coefficient from 7 to 91 days compared to the corresponding binary binder mix; 0.55 compared to 0.38 $kg/m^2h^{0.5}$ respectively, however, as mentioned, this is not so much an advantage because the magnitudes were still higher than that of UWC-G40 and UWC-C.

As with the ggbs mix, the ternary binder mix incorporating fly ash (UWC-TB-F20) gave a higher 7 and 91-day but a lower 28-day coefficient compared to both the binary binder mix (UWC-F20) and the control mix. Again, as with ggbs, no synergistic effect could be noticed due to the presence of limestone powder, however it did result in a larger decrease in sorptivity coefficient from 7 to 91 days compared to the binary binder mix; 0.75 compared to 0.34 $kg/m^2h^{0.5}$ respectively. The corresponding SCC mix (SCC-TB-F20) also had a higher early-age (7-day) sorptivity coefficient compared to it binary binder mix (SCC-F20) however, unlike UWC-TB-F20, its long-term (91-day) sorptivity coefficient was similar to both its control and binary binder mix. As with the FC mixes, the presence of limestone powder in UWC did not have any noticeable positive effects on the sorptivity but instead increased the coefficients indicating greater water absorption.

A similar trend to that found with both SCC and FC mixes exists between the sorptivity coefficient and the cube compressive strength of UWC mixes (Figure 8-15), but with greater scatter; R^2 of 0.506 compared to R^2 of 0.713 and 0.615 for SCC and FC respectively.

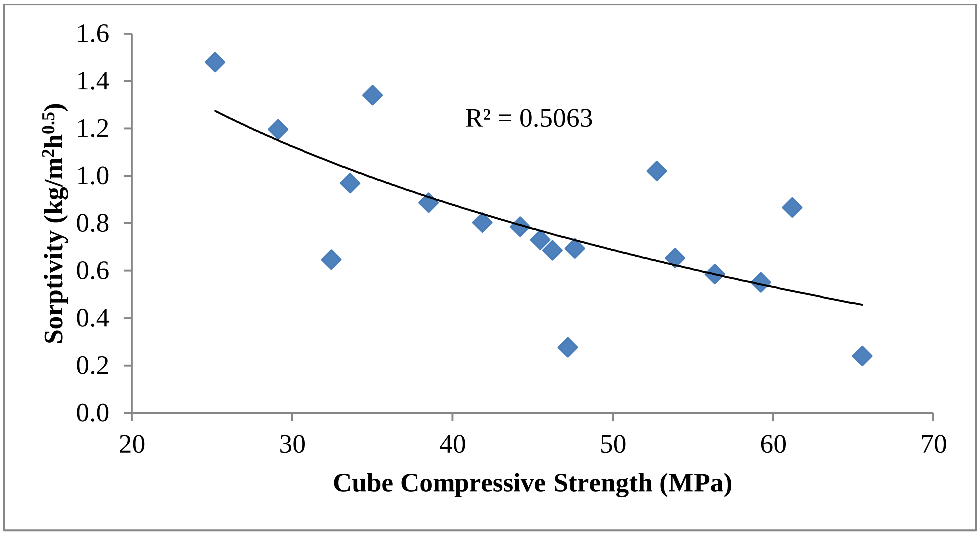


Figure 8-15 Relationship between sorptivity coefficient (short-term) and the cube compressive strength of UWC mixes

8.2.2.2 Rapid chloride penetration test

The total charge passed values reduces with increase in age of concrete for all mixes indicative of the positive effects of curing. The results are given in Table 8-8 and illustrated in Figure 8-16.

8.2.2.2.1 Binary binder mixes

The binary binder mix with 20% limestone powder (UWC-L20) attained, considering the repeatability coefficient, similar values of charge passed to the control mix at all ages. The 7-day charge passed was similar to and more than double that obtained for the corresponding SCC and FC mixes respectively, however, unlike both SCC and FC, there is a sharp drop in the values of charge passed from 7 to 28 days with a much smaller decrease from 28 to 91 days; 9913 compared to 279 Coulombs respectively (Figure 8-16). The 91-day value of charge passed was similar to that of FC-L20 mix which is half that for SCC-L20 though the value is still high achieving a rating of “Moderate” according to ASTM C1202 (2007) (Table 8-8).

The mix with ggbs (UWC-G40) attained, as with FC-G40, a lower value of charge passed at 7 days compared to the control mix, with similar 28 and 91-day values. As mentioned, the mix SCC-G40 attained a similar 7-day value but, as with both FC and UWC, lower values at 28 and 91 days compared to their corresponding control mix. The mix UWC-G40 achieved a rating of “Low” at 91 days whereas the SCC and FC mixes both achieved “Very Low” ratings. Similar to the trend observed with FC and in UWC-L20, there is more significant drop in value of charge passed from 7 to 28 days, though smaller than that of UWC-L20, with a relatively smaller difference between the 28 and 91-day values; 2155 compared to 504 Coulombs respectively.

The fly ash mix, UWC-F20 attained a lower 7 and 91-day, though similar 28-day values of charge passed compared to the control mix. As with both SCC and FC mixes, the UWC-F20 mix also achieved an excellent rating of “Very Low” at 91 days (Table 8-8). Unlike both SCC and FC mixes, in the case of UWC the values of charge passed for the binary binder mix with fly ash was lower than those obtained for that with ggbs. This again could be attributed to the fact that with UWC, the fly ash mix consistently had a slightly higher compressive strength (3-5 MPa) than the ggbs mix, contrary to that observed with SCC and FC, which could be indicative of a denser matrix hence the lower values of charge passed at all ages.

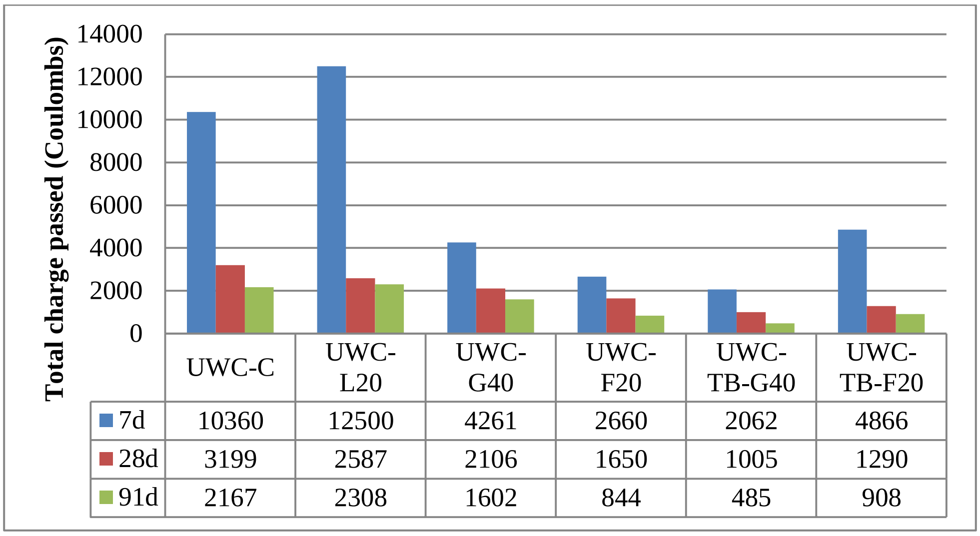
Table 8-8 Rapid chloride penetration test results for UWC mixes

			Total charge passed (Coulombs)			**Rating according to ASTM C1202** (2007)		
Binder	**Mix no./Age (days)**		**7**	**28**	**91**	**7**	**28**	**91**
Control (PC)	27	0%	10360	3199	2167	High	Moderate	Moderate
Limestone	28	20%	12500	2587	2308	High	Moderate	Moderate
GGBS	29	40%	4261	2106	1602	High	Moderate	Low
Fly Ash	30	20%	2660	1650	844	Moderate	Low	Very Low
Ternary Binder-GGBS	31	40%	2062	1005	485	Moderate	Low	Very Low
Ternary Binder- Fly Ash	32	20%	4866	1290	908	High	Low	Very Low

8.2.2.2.2 Ternary binder mixes

The ternary blended binder mix UWC-TB-G40 had lower values of charge passed compared to both its binary binder mix (UWC-G40) and the control mix at all ages. Comparing the ratings given in Table 8-8, it can be seen that the ratings of the ternary binder mix has improved at all ages; for instance the 7 and 91-day ratings of the of UWC-G40 was “High” and “Low” respectively whereas for the UWC-TB-G40, the ratings improved by one level to “Moderate” and “Very Low” respectively.

The ternary binder mix incorporating fly ash (UWC-TB-F20), unlike that with ggbs, attained similar values of charge passed compared to its binary binder mix (UWC-F20) at all ages. Though referring to Table 8-8, it can be seen that, with the inclusion of limestone powder, the 7-day rating was worse than that of the binary binder mix whereas the 28 and 91-day ratings improved, however due to the high repeatability for this test, the difference between the values of charge passed for the two mixes was less than the repeatability hence they are not significantly different even though the ratings paint a different picture. Both SCC and FC ternary binder mixes, as with UWC, achieved similar or lower values of charge passed compared to their corresponding binary binder mixes. As mentioned, achieving a ternary binder mix with a similar performance can lead to both economic and environmental advantages; reduction in cost and reduced carbon footprint respectively due to lower Portland cement content. Further analysis and discussions of this is given in Chapter 9.



	UWC-C	UWC-L20	UWC-G40	UWC-F20	UWC-TB-G40	UWC-TB-F20
🟦 7d	10360	12500	4261	2660	2062	4866
🟥 28d	3199	2587	2106	1650	1005	1290
🟩 91d	2167	2308	1602	844	485	908

Figure 8-16 Total charge passed of UWC mixes with different binder compositions

No correlation was noticed between the values of total charge passed and the cube compressive strength of the mixes (Figure 8-17). A similar conclusion was drawn for SCC (Figure 7-18) and FC (Figure 8-8) mixes.

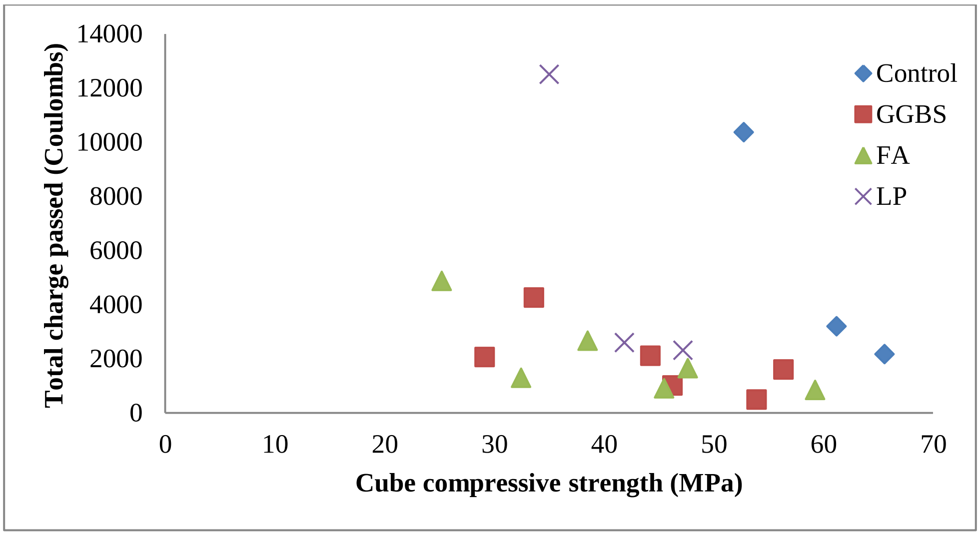


Figure 8-17 Relationship between the RCP test results and cube compressive strength for UWC mixes

8.3 Conclusions

This chapter presented test results on fresh and hardened properties of FC and UWC mixes with binary and ternary blended binders containing ggbs, fly ash and limestone powder; all the cement replacements were by volume. Only the optimum replacement levels of ggbs and fly ash (40 and 20% respectively), obtained from previous tests on SCC (Chapter 7), were used to produce the binary and ternary mixes. The conclusions drawn from this investigation are given in this section.

1. **Fresh property tests**

- All the FC and UWC mixes attained the required target fresh properties. In both cases, with the incorporation of additions, achieving those properties required a decrease in the SP dosage; consistent with SCC. Additionally, in the case of UWC, an increase in the AWA dosage was needed to achieve the target washout.

- The FC mixes had similar plastic viscosity values as SCC but with higher values of yield stress. As for UWC, both the yield stress and plastic viscosity values were higher than for both FC and SCC mixes. The mixes had a ‘sticky’ nature due to the addition of AWA.

2. **Strength tests**

- All binary binder FC and UWC mixes with ggbs, fly ash and limestone powder attained lower early-age and long-term strengths compared to the their respective control mixes unlike SCC. As mentioned this could be due to the higher water/cement ratio of FC and UWC. Unlike SCC and FC mixes, the UWC fly ash mix (UWC-F20) attained slightly higher strengths at all ages compared to the ggbs mix (UWC-G40).

- The strength development rate of FC mixes with all three additions, between 28 and 91 days, was similar to that of the control mix hence the probability of either of the mixes achieving a similar strength to the control mix at later ages is low. However for the UWC mixes, of the three additions, the strength development rate of the fly ash and ggbs mixes (UWC-F20 and UWC-G40) were higher than that of the control mix hence, unlike FC, there is therefore a good chance for these mixes to achieve similar or even higher strengths compared to the control mix at later ages.

- Both FC and UWC ternary binder mixes attained lower compressive strengths at all ages up to 91 days compared to their respective binary binder mixes with the exception of UWC ternary binder ggbs mix (UWC-TB-G40) which attained similar compressive strengths compared to UWC-G40 mix at 28 and 56 days.

- The ternary binder ggbs mixes FC-TB-G40 and UWC-TB-G40 had a similar strength development rate to their respective binary binder mix up to 56 days, but a lower rate from 56 to 91 days. Hence in both cases, given their lower compressive strength at 91 days, it is unlikely that the strength of the ternary binder mixes will reach that of the binary binder mixes at later ages. Unlike ggbs, for fly ash, the ternary binder mixes had a slightly higher strength development rate compared to their respective binary binder mixes. The difference in compressive strength between the ternary and binary binder mixes at 91 days was about 4 and 9 MPa for FC and UWC respectively; hence as with ggbs, it is doubtful that the ternary binder mixes would achieve similar strengths to the binary binder mixes at later ages.

- As recommended in the literature, all the UWC tremie cast cubes attained a compressive strength ratio of 80% or higher relative to the respective air cast cubes. Good linear correlation was obtained between the compressive strength of air versus tremie cast cubes ($R^2 = 0.917$).

- As with SCC, good correlations were obtained between the cube compressive and tensile splitting strength of concrete, with the results falling within the ranges given by Eurocode 2 and CEB-FIB Model 90 design codes for normal-consistence concrete. Correlations were also obtained between the cube compressive strength and the results of the non-destructive tests. For FC, the UPV results had a good fit with a typical correlation given in the literature for normal-consistence concrete but, as with SCC, the dynamic elastic modulus results, although following the same trend, were lower (by about 5 GPa). Unlike FC, the UPV results of UWC were, for a given compressive strength, lower than the typical correlation (by about 0.25 km/s). As with both SCC and FC, the dynamic elastic modulus results of UWC were also lower than the correlation given in the literature (by about 10 GPa).

3. Durability tests

- Binary binder FC mixes with fly ash and limestone powder gave higher early age sorptivity coefficients whereas ggbs mixes gave similar values to the control mix. The ggbs and limestone powder mixes attained similar long-term (91-day) coefficient as the control mix whereas the fly ash mix still had a higher sorptivity value. As with FC, the limestone powder UWC mix (UWC-L20) attained higher 7-day but similar 91-day coefficient to the control mix. Fly ash and ggbs mixes both attained similar coefficients at 7 and 28 days but surprisingly higher values at 91 days compared to the control mix. As with SCC, both the limestone powder mixes, FC-L20 and UWC-L20, had the greatest reduction in sorptivity coefficient from 7 to 91 days compared to the other binary binder mixes.

- For both FC and UWC, the inclusion of limestone powder in ternary binder mixes resulted in higher sorptivity coefficients than the respective binary binder mixes at both 7 and 91 days. Hence unlike SCC, in this case no synergistic or positive effects were noticed with using the ternary binder combination.
- In general, the sorptivity coefficients of FC and UWC mixes were higher than SCC which could be due to the lower water/cement ratio of SCC. As with SCC, for both FC and UWC, good correlation exists between the

sorptivity coefficients and the compressive strength of the concrete. However unlike SCC, here sorptivity coefficients reduce with the age of concrete; indicative of the positive effects of curing.

- The limestone powder mix (FC-L20) attained similar values of charge passed to the control mix at 7 days but higher 28 and 91-day values. With ggbs lower charge passed was attained at all ages compared to the control mix. Fly mixes attained similar 7 and 28-day values and a lower 91-day value to the control mix. Unlike FC, the UWC with limestone powder (UWC-L20) attained similar values of charge passed to the control mix at all ages. As with FC, the ggbs mix UWC-G40 attained a lower charge passed at 7 days compared to the control mix but with similar values at 28 and 91 days. The fly ash mix (UWC-F20) attained a lower value of charge at 7 and 91 days with similar value at 28 days.

- Both FC and UWC ternary binder mixes with ggbs and fly ash attained similar or lower values of charge passed relative to their respective binary binder mix and all had ratings of ‘Very Low’ at 91 days according to ASTM C1202 (2007). Hence unlike the sorptivity results, in this case there is an advantage of using ternary binder combinations as concrete with similar performance can be obtained with higher Portland cement replacement resulting in economic and environmental advantages.

- As with sorptivity, for both FC and UWC curing had a positive effect on the values of charge passed, reducing with increase in age however, as with SCC and unlike the sorptivity results, no correlation exists between the charge passed and cube compressive strength.

Chapter 9 Overall Discussion

In Chapter 7 andChapter 8, the results of tests investigating the effect of different binder compositions on the fresh, hardened mechanical and durability properties of different types of high-consistence concrete i.e. SCC, FC and UWC were reported. In this chapter, the entire set of test results are combined and analysed in terms of:

- **Fresh properties:** Looking at the effect of different binder compositions on admixture dosages. In addition looking at the relationships between the slump, slump flow and flow table values and comparing these with those in the literature.

- **Rheological properties:** Comparing the ranges of yield stress and plastic viscosity with those reported in the literature.

- **Hardened mechanical properties:** Comparing the compressive strength ratio of mixes (relative to their respective control mix) and looking at the relationships between the tensile splitting strength, ultrasonic pulse velocity and dynamic elastic modulus with compressive strength and comparing these with those in the literature.

- **Durability properties:** Looking at the relationship between the sorptivity and RCP test results and compressive strength. In addition comparing the attained values with specify criteria given in the literature and commenting on the suitability of these criteria.

- **Embodied carbon content:** Comparing the level of total embodied carbon content of the mixes with different binder compositions and also looking at the embodied carbon content per unit strength.

The above analysis also allows for similarities or differences between the three types of high-consistence concrete to be observed.

9.1 *Fresh properties*

The target properties for SCC were based on the European guidelines (EFNARC, 2005) and were adequate for normal applications. The chosen target values were an average slump flow value of 700mm (Class SF2), a V-funnel time of around 8s (Class VF2), a J-ring step height of less than 15mm using a narrow-gap J-ring (41mm bar spacing) (Class PA2) and a segregation index of less than 15% (Class SR2).

A slump value of 200 – 240mm was chosen as the target fresh property for FC. As in FC, a similar slump value range was chosen for UWC with a washout resistance of ≤ 15%. In addition to the slump, all the mixes achieved a slump flow of 390 – 470mm and flow diameters of about 400 – 550mm (Class F3 and F4) with the flow table test. The relationship between slump and slump flow values (Figure 9-1) and the range of slump flow and flow table values (Figure 9-2) are similar to those given in Domone (1998).

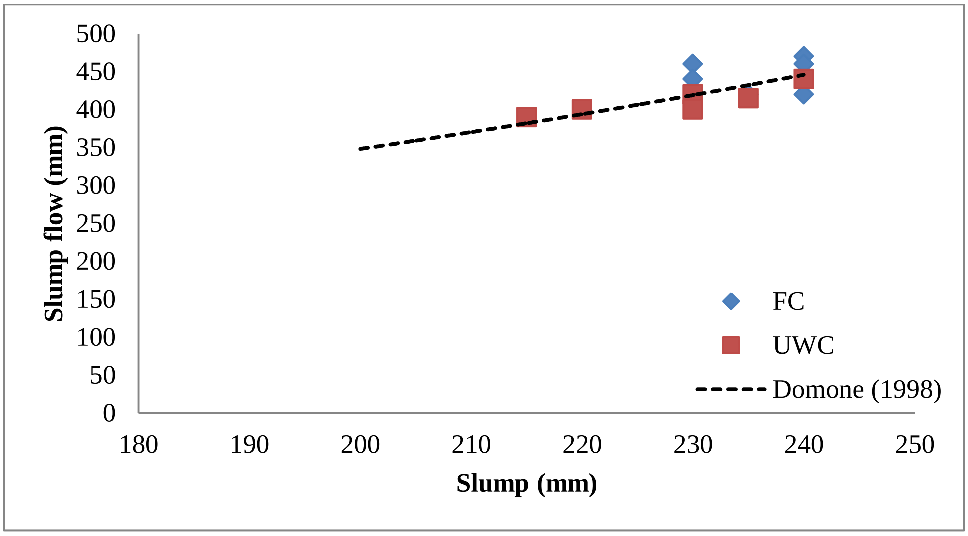


Figure 9-1 Relationship between slump and slump flow results

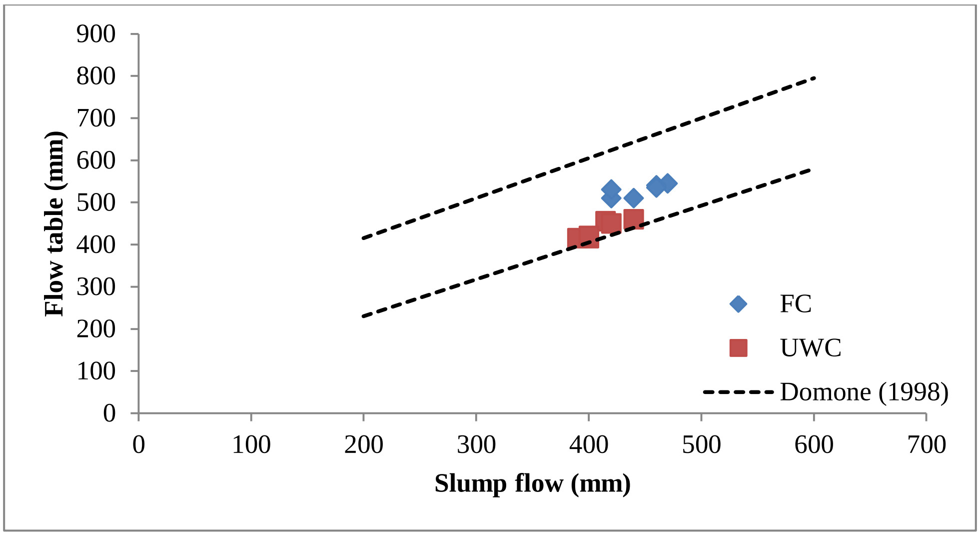


Figure 9-2 Relationship between slump flow and flow table results

For all three, the addition of superplasticiser was required to achieve the required fresh properties, but the required dosage reduced with increasing replacement levels of additions i.e. ggbs, fly ash and limestone powder. The maximum reduction of 0.8% of admixture by weight of powder (from 1.5 to 0.7%) was seen in ternary binder SCC with 80% fly ash. For the same replacement level with ggbs the reduction was lower at 0.6%. The corresponding binary binder mixes had slightly lower reductions of 0.7% and 0.5% respectively. As mentioned in 2.4.2.1, the smooth spherical shape of fly ash particles leads to easier particle movement hence an improvement in consistence, or in this case a reduction in the SP dosage for the same consistence.

For SCC and UWC due to the requirement of segregation resistance and washout resistance respectively, in addition to superplasticiser, a viscosity modifying agent (VMA) and an anti-washout admixture (AWA) were used. The VMA dosages ranged from 0 for the control SCC mix to 0.3% for ternary binder mixes with 60 and 80% fly ash. Ternary binder mixes with ggbs had a similar VMA dosage of 0.2%. However the binary binder mixes with both ggbs and fly ash required a lower dosage on average of 0.1%. The addition of ggbs or fly ash i.e. binary binder resulted in some bleeding, hence the need for the VMA as expected, however, the incorporation of limestone powder, i.e. to give a ternary binder, increased the bleeding hence a higher VMA dosage was required. The AWA dosages in the UWC ranged from 0.5 to 0.7%, which is, on average, almost three times the VMA dosage. As with SCC, the UWC control mix had the lowest dosage and the binary binder mix with fly ash had the highest dosage; the binary binder mix with ggbs and both the ternary binder mixes had a dosage of 0.6%. Both the VMA and the AWA increase the viscosity of the mix hence reduce the fluidity, as expected, when all other variables are kept unchanged (Figure 6-7 and Figure **6-10** respectively). The AWA also resulted in the mix being more 'sticky' with a slower creep (deformation rate), hence the time taken for the concrete to collapse and achieve the required slump was almost three times longer than in FC.

9.2 Rheological properties

Figure 9-3 illustrates the typical flow curves obtained from the two-point test for each type of concrete i.e. SCC, FC and UWC. Similar trends were obtained by Chai (1998) (Figure 9-4). Here the speed and torque data were used before conversion to shear stress and shear rate respectively, for comparison with Chai's data. As mentioned in 4.3.2.5, the intercept on the torque axis (g) and the gradient (h) of the torque/speed relationship relate to the yield stress and the plastic viscosity respectively. It can be seen in Figure 9-3 that the SCC and FC have lower values of g compared to UWC which means that they have lower yield stress hence they flow more easily under their own weight. The values of h (the inverse slope with the graph plotted as shown) are higher for SCC and UWC indicating higher plastic viscosity which is due to the requirements of segregation resistance and washout resistance respectively.

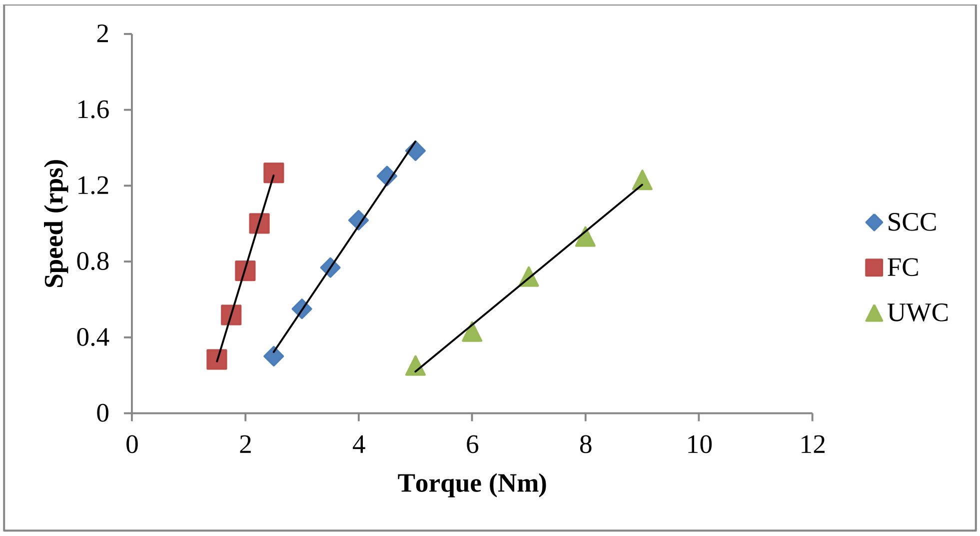


Figure 9-3 Example flow curves of two-point test for SCC, FC and UWC

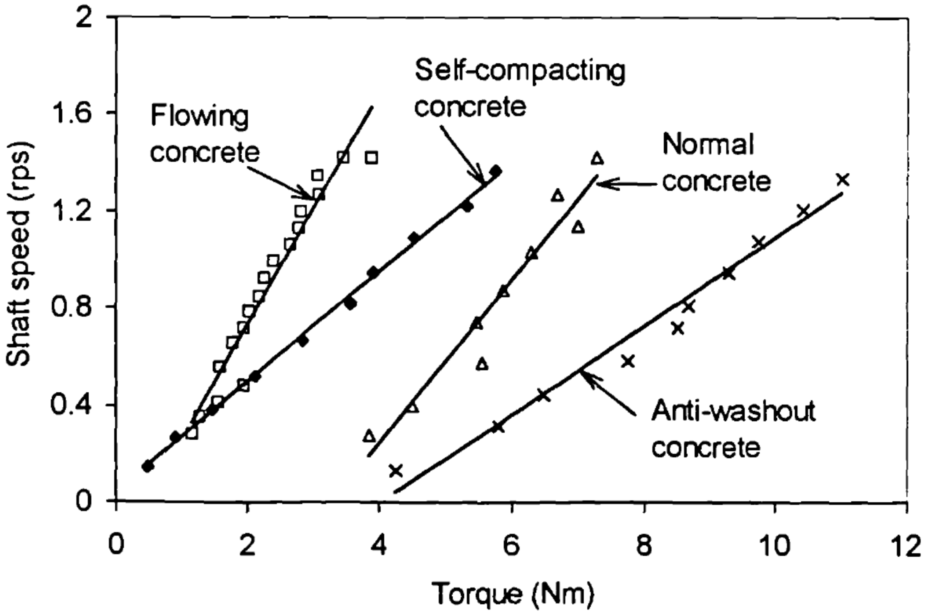


Figure 9-4 Typical flow curves of two-point test for different types of concrete (Chai, 1998)

The Bingham constants of the mixes are plotted in Figure 9-5. Most SCC mixes have plastic viscosity values in the range of 10 – 40 Pas with yield stress values of less than 100 Pa, however a number of mixes attained higher values of both, with maximum values being about 70 Pas and 300 Pa respectively. FC mixes attained plastic viscosity values of around 20 Pas with yield stress values of around 150 – 200 Pa. The UWC mixes had both higher plastic viscosity and yield stress values compared to SCC and FC ranging between 40 – 70 Pas and 200 – 500 Pa respectively. The relative rheology of the SCC and FC mixes are similar to that given in the literature (Figure 9-6).

The FC mixes have a higher yield stress than SCC. The yield stress of SCC has to be very low to ensure its ability to flow under its own weight and to fill the required space. The yield stress of UWC is higher than both SCC and FC which could be due to both the lower consistence and the 'sticky' nature of the mix. SCC and UWC mixes have a higher plastic viscosity value to ensure mix stability, i.e. segregation resistance and washout requirements respectively, although the plastic viscosity of UWC is generally higher than SCC as expected from the 'sticky' nature of the mix.

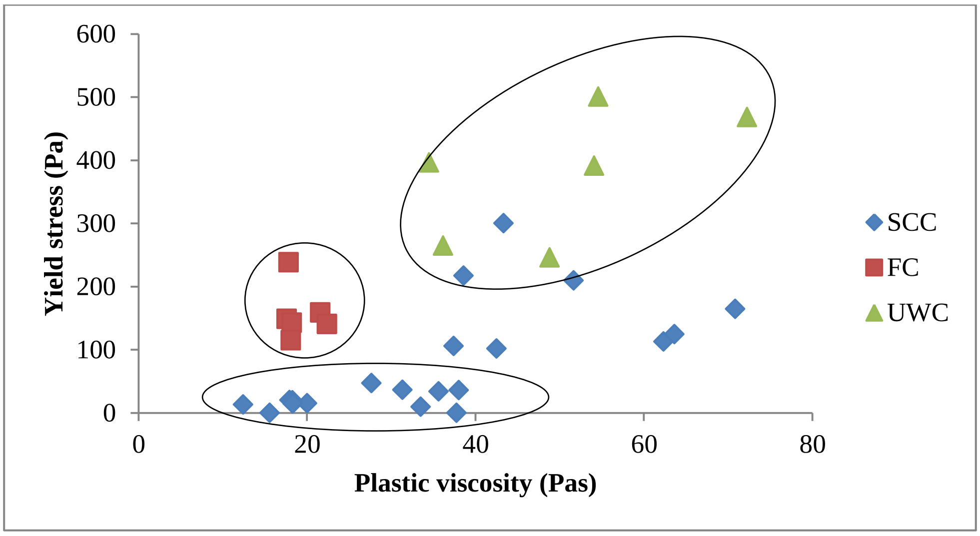


Figure 9-5 Rheology of SCC, FC and UWC

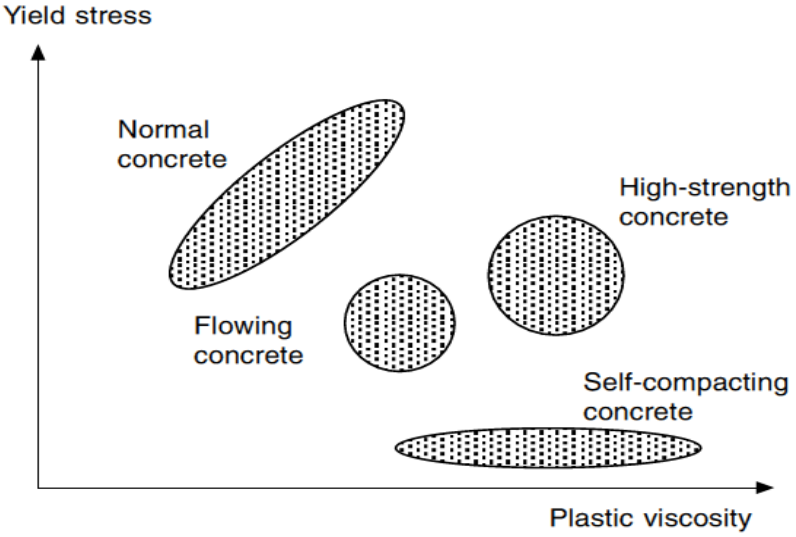


Figure 9-6 Rheology of several types of concrete (Newman & Choo, 2003)

9.3 Hardened mechanical properties

In this section the compressive strength ratios of mixes with additions with respect to the control mix are discussed. In addition the relationship between the compressive strength and the splitting tensile strength and the non-destructive tests for all three concrete types are also discussed.

9.3.1 Compressive strength ratio

The ratio of compressive strength of mixes with additions to those of the control mix is shown in Table 9-1. For the binary binder mixes it is clear from this that the replacement of Portland cement with additions leads to a reduction in compressive strength with the reduction being greater at higher replacement levels. For SCC, as expected and concluded in Chapter 7, the strength reduction at ages up to 91 days, for the same addition level, was greater with fly ash than with ggbs (Uysal & Sumer, 2011; Gesoğlu et al., 2009; Demirboğa et al., 2004). For FC, the strength reduction of the ggbs mix was also lower than the fly ash mix even though the replacement level was double (40 compared to 20%). However, the opposite was the case for UWC. Comparing the performance of the three types of concrete, for the same addition level, the strength reduction for FC and UWC at early ages is greater than that of SCC with the exception of FC-L20. This could be attributed to the lower water/cement ratio of SCC having a higher rate of early hydration resulting in higher strength gain at early ages.

At 91 days, SCC ggbs mixes with up to 40% replacement and fly ash mix with 20% replacement achieved similar or higher strengths to the control mix (strength ratio greater than 1) whereas for FC and UWC neither the ggbs nor the fly ash mix was able to achieve similar strengths to the control mix. The rate of strength gain of SCC between 7 and 91 days is higher than in FC and UWC. This again could be due to the lower water/cement ratio of SCC where the increased rate of initial hydration results in a higher rate of and earlier initiation of the pozzolanic reaction leading to quicker strength gain, and also due to the higher cement content, sufficient calcium hydroxide is produced to carry on the pozzolanic reaction up to and after 91 days.

The SCC ternary binder mixes with 40% ggbs and 20% fly ash both achieved higher 91-day strengths (by about 5%) than both the control mix and their respective binary binder mixes; however, on the contrary, FC and UWC ternary binder mixes achieved lower strengths as their respective control mixes and binary binder mixes.

Table 9-1 Compressive strength ratio of mixes with additions with respect to the control mix

		Compressive strength ratio								
		SCC			FC			UWC		
Binder	**Replacement level (%)**	**7**	**28**	**91**	**7**	**28**	**91**	**7**	**28**	**91**
Control (PC)	0%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Limestone	10%	0.90	0.96	1.06						
	20%	0.73	0.79	0.94	0.81	0.83	0.81	0.66	0.68	0.72
	30%	0.74	0.83	0.92						
GGBS	20%	0.97	0.99	1.05						
	40%	0.75	1.05	1.00	0.76	0.92	0.91	0.64	0.72	0.86
	60%	0.63	0.77	0.87						
	80%	0.54	0.74	0.69						
Fly Ash	20%	0.82	0.95	1.01	0.59	0.68	0.73	0.73	0.78	0.90
	40%	0.67	0.84	0.87						
	60%	0.30	0.47	0.53						
	80%	0.09	0.13	0.20						
Ternary Binder-GGBS	20%	0.72	0.91	1.09						
	40%	0.69	0.91	1.05	0.58	0.76	0.76	0.55	0.76	0.82
	60%	0.62	0.82	0.89						
	80%	0.53	0.70	0.71						
Ternary Binder- Fly Ash	20%	0.69	1.10	1.05	0.54	0.62	0.67	0.48	0.53	0.69
	40%	0.45	0.70	0.73						
	60%	0.22	0.43	0.49						
	80%	0.06	0.11	0.15						

Hence in terms of strength, the use of ternary blended binders in SCC has advantages as it is possible to achieve similar or higher strength than the respective binary binder mix with higher cement replacement. In this project, a maximum increase of 5%, relative to the binary binder mixes, was obtained with two of the ternary binder mixes, one incorporating 40% ggbs and another 20% fly ash. In addition, due to the incorporation of limestone powder, the total replacement level of these two mixes was 12 and 16% higher than those of the binary binder mixes i.e. 52 and 36% respectively. However this was not the case for FC and UWC as the ternary binder mixes achieved lower strength than both the control and the respective binary binder mixes.

9.3.2 Tensile splitting strength

The relationship between the cube compressive strength and cylinder splitting strength for all three types of concrete tested in this project is shown in Figure 9-7. It can be noticed that nearly all the results fall within the typical ranges given by both BS EN 1992-1-1 (EC2) (2004) and CEB FIB Model 90 (1993). This shows that in addition to being independent of the powder combination and testing age, it is also independent of the type of concrete. The FC data seems to fit well with the EC2 mean whereas the SCC and UWC data seem to fall to the right of the line (between the mean and the 95% fractile), hence the mean of the whole data set deviates to the right of the EC2 mean as the tensile splitting strength increases.

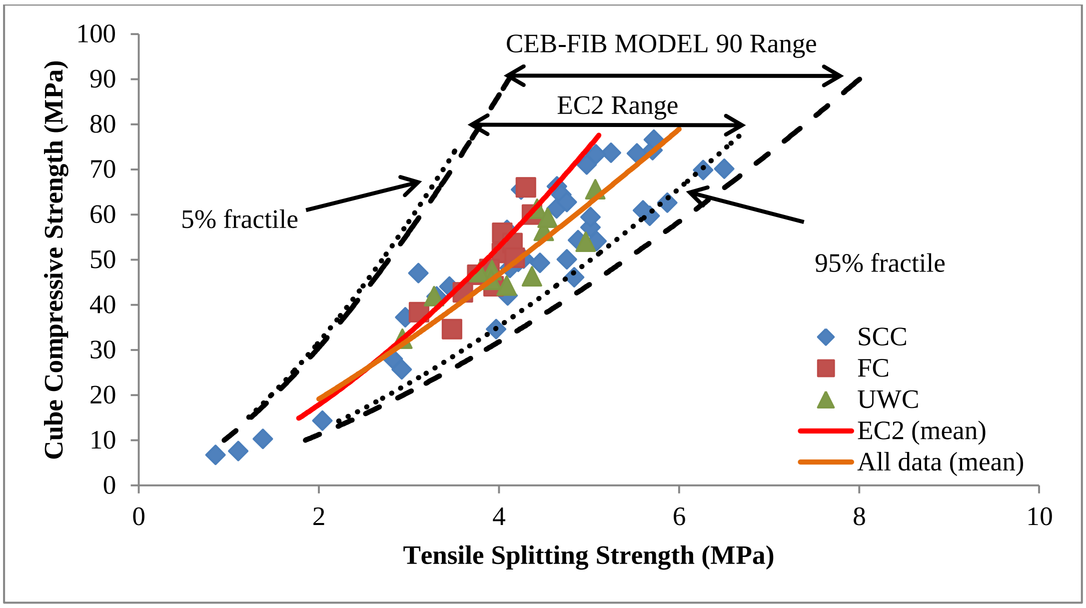


Figure 9-7 Relationship between compressive strength and cylinder splitting strength for SCC, FC and UWC

9.3.3 Non-destructive test results

The relationship between the cube compressive strength and the UPV for all the mixes in this project is shown in Figure 9-8. The majority of the data fall within the upper and lower limits of data previously obtained at UCL (red lines) for normal-consistence concrete (Domone & Illston, 2010). Similar results were also obtained by Gesoğlu et al. (2009). Overall it can be said that the UPV results are related to the strength of concrete which has advantages such as allowing, with the use of these relationships, the strength of concrete to be estimated at any age which in turn can be used to make an initial assessment of in-situ concrete saving both time for testing and cost as it is less expensive than taking cores.

Similarly Figure 9-9 shows the relationship between the compressive strength and the dynamic elastic modulus results for all mixes in this project. As mentioned previously, for the same compressive strength, the dynamic elastic modulus results, for all three types of concrete tested, were consistently lower compared to those previously obtained at UCL. For SCC and UWC, the lower stiffness was thought to be consistent with the lower coarse aggregate content however surprisingly FC also gave lower values even though its aggregate content was similar to that of normal-consistence concrete. For comparison the static elastic modulus equations for normal-consistence concrete from EC2 and CEB FIB Model 90 design codes were used to obtain the corresponding dynamic elastic modulus values for various compressive strengths; the ratio of static to dynamic elastic modulus ranges from 0.8 – 0.85, hence here the dynamic elastic modulus was calculated by dividing the static elastic modulus by factor of 0.825 (average) (Domone & Illston, 2010). These results, as can be seen on Figure 9-9, are consistently lower (by about 5 GPa) than the results obtained at UCL and are a very good match to the SCC results.

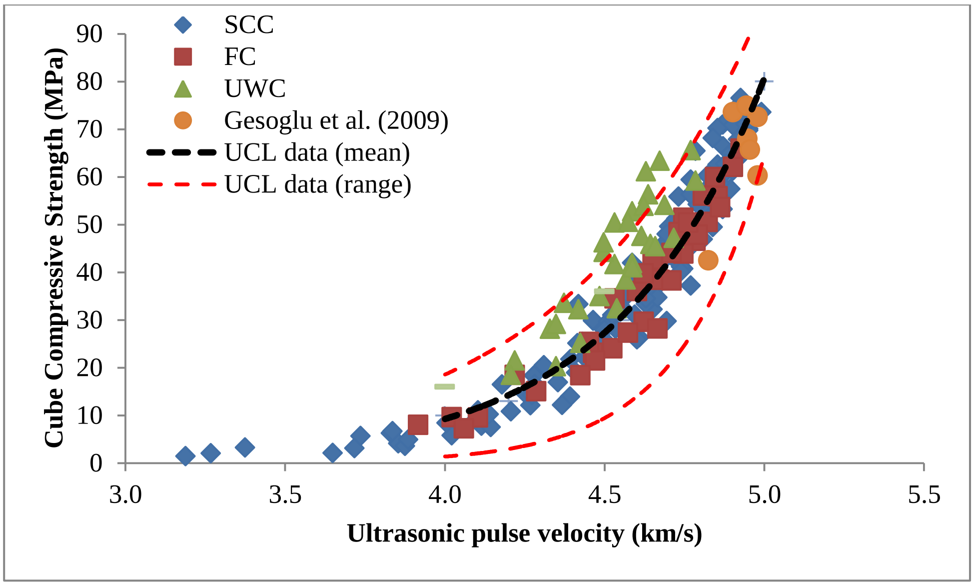


Figure 9-8 Relationship between compressive strength and UPV results for SCC, FC and UWC

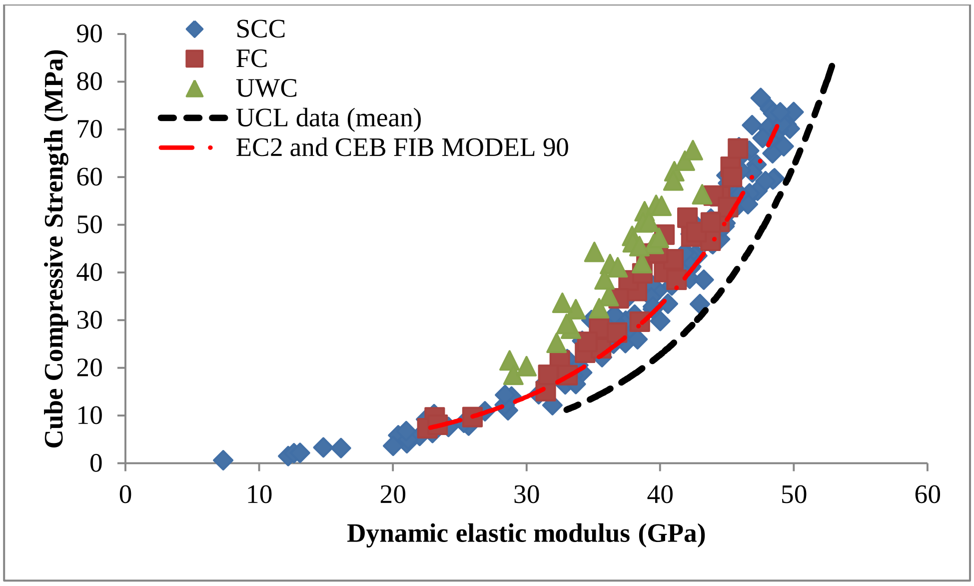


Figure 9-9 Relationship between the compressive strength and the dynamic elastic modulus results for SCC, FC and UWC

9.4 Durability properties

This section gives and compares relationships between the compressive strength and the measured durability parameters i.e. sorptivity coefficient and total charge passed for SCC, FC and UWC.

9.4.1 Sorptivity

Figure 9-10 shows the relationship between sorptivity coefficient and the compressive strength for SCC, FC and UWC mixes together with similar data for normal-consistence concrete (NCC) from literature. For the HCC mixes, it can be seen that the data points for all the three types of concrete overlap; for a compressive strength of 25 – 65 MPa the sorptivity coefficient ranges from 1.5 – 0.25 $kg/m^2h^{0.5}$ respectively. The general trend is the sorptivity decreases with increasing compressive strength which is attributed to the denser pore structure of higher strength concrete. The rate of change of sorptivity going from 80 – 20 MPa is relatively constant however this changes (increases) significantly below 20 MPa. As mentioned earlier, the relationship between the sorptivity and compressive strength is independent of powder combination and testing age, however in addition, referring to Figure 9-10, it can be said that it is independent of type of high-consistence concrete.

For the same compressive strength, the sorptivity coefficients in the literature (Gopalan, 1996; Alexander & Magee, 1999) for NCC (at 28 days) are higher than those obtained for the HCC mixes. Also it can be seen that for NCC, the incorporation of additions led to a reduction in the sorptivity coefficient for similar compressive strengths; this is expected as reducing the PC content by incorporating additions would result in a denser microstructure being formed due to the secondary reactions hence the lower sorptivity. Comparing the NCC mixes with no additions, those with lower strengths, i.e. higher water/cement ratio, have a higher sorptivity coefficient compared with higher strength mixes, as expected, because increasing the water/cement ratio would increase the number of larger voids in the microstructure, hence the higher sorptivity coefficient. Therefore from these results, it is beneficial to use additions as this would not only reduce the amount of PC but also, for the same compressive strength, give a lower sorptivity coefficient. However no similar conclusions can be drawn from HCC results as, surprisingly, no significant difference was seen with variations in water/cement ratio or powder combinations. The degree of scatter is higher for the NCC compared to HCC mixes.

Unlike the tensile splitting test or the non-destructive tests, there are no typical correlations given within the literature for the sorptivity test. As for knowing what value of sorptivity coefficient is good or what is bad, only one acceptance limit has been suggested, by Beushausen et al. (2006), which is that the sorptivity coefficient for a laboratory concrete must be less than 6 $kg/m^2h^{0.5}$; this limit is also included in The Concrete Society technical report (TR 31) on permeability testing of site concrete (2008). Hence considering this limit, all the concrete mixes in this project attained not only acceptable sorptivity coefficients but many values are one fifth of this, which one would expect to correspond to an excellent performance. The authors mention that this acceptance value is an outcome of 15 years of extensive laboratory and on-site research in South Africa however the work and results used for producing this acceptance value were unavailable. In general, there is a need for greater research looking at the relationships between the sorptivity coefficient and other durability properties of concrete such as chloride penetration and corrosion resistance and also the expected differences in sorptivity coefficients between laboratory and site concrete. In addition as the sorptivity test is sensitive to the initial moisture state of the concrete, tests should be done using the different drying regimes available and differences in values between the different regimes reported hence a more realistic acceptance criterion could be produced for each drying regime or alternatively a common internationally recognised drying regime should be put in place. Therefore in this project the sorptivity values were only used as a durability index to compare the performance of the different concrete mixes.

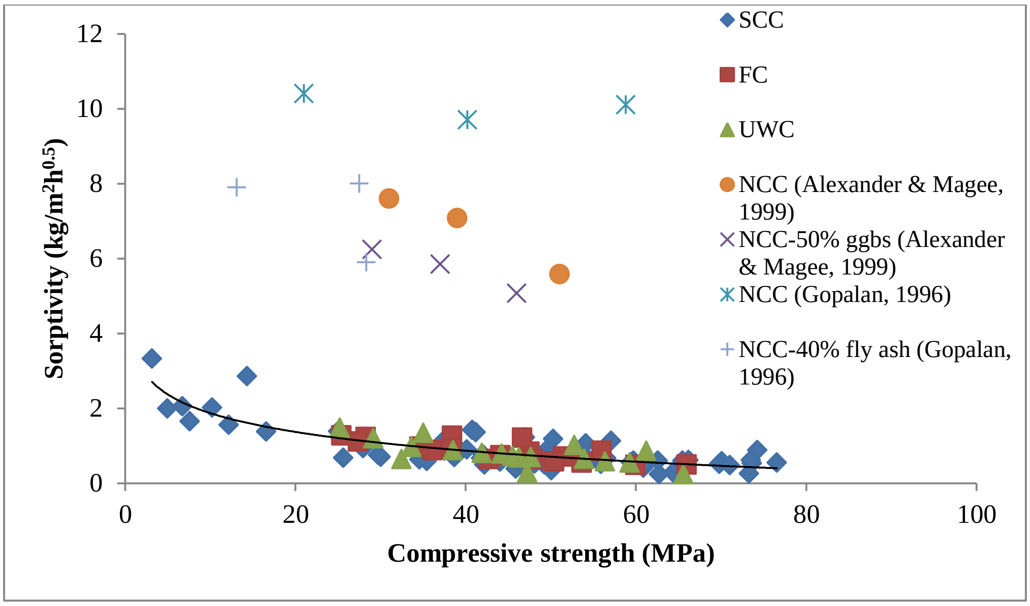


Figure 9-10 Relationship between the sorptivity coefficient and the cube compressive strength for SCC, FC and UWC

9.4.2 Rapid chloride penetration test

The RCP test results for all the mixes are plotted against their respective compressive strength values in Figure 9-11. As mentioned previously, no correlation can be noticed between these two values. The degree of scatter is very high, for instance for a compressive strength of 50 MPa the total charge passed ranges from around 500 to over 10000 Coulombs. This could be attributed to the fact that, unlike sorptivity, this test is greatly affected by variations in the chemistry of the pore solution from the different powder combinations and also different types of additions may alter the microstructure in different ways. Additionally the test repeatability value of about 34% could also contribute to the scatter. The scatter is high for strengths up to 60 MPa but significantly lower thereafter.

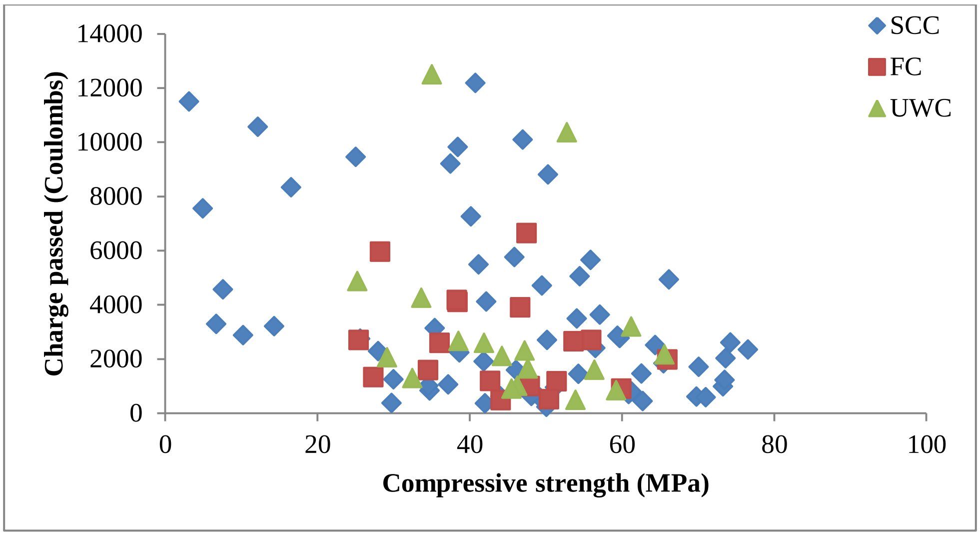


Figure 9-11 Relationship between the total charge passed and the cube compressive strength for SCC, FC and UWC

The sorptivity coefficients are plotted against the values of charge passed for all mixes in Figure 9-12. It appears that a correlation, though weak, exists between these two, and a linear correlation (R^2=0.294) may be the most suitable. Kanellopoulos et al. (2012) obtained a similar linear correlation though the sorptivity values were calculated in different units. SCC mixes displayed higher scatter compared to FC and UWC but this could be simply due to the higher number of mixes tested. However the overall degree of scatter increases significantly over 3000 Coulombs.

Both Figure 9-11 and Figure 9-12 show that the degree of scatter is lower for higher quality concrete with a dense pore structure i.e. high strength (60 – 80 MPa) and charge passed <3000 Coulombs respectively. However in both figures, the degree of scatter is high. One of the main criticisms of this test is that the amount of charge passed is not only due to chloride ions but also other ions within the pore solution which are being ‘forced’ through due to the applied potential difference and we know that the incorporation of additions can result in a change in the pore chemistry. Therefore it would not be correct to compare mixes with different additions as their pore chemistry could be different. Also, as with the sorptivity test, a better understanding of the relationship of this with other durability properties is needed. Considering all these, the author believes that this test is not suitable for use as a durability indicator when comparing mixes with different binders but perhaps can be used with caution, in laboratory conditions, to compare mixes with different levels of the same addition or to check the production consistency of a mix with the same binder composition.

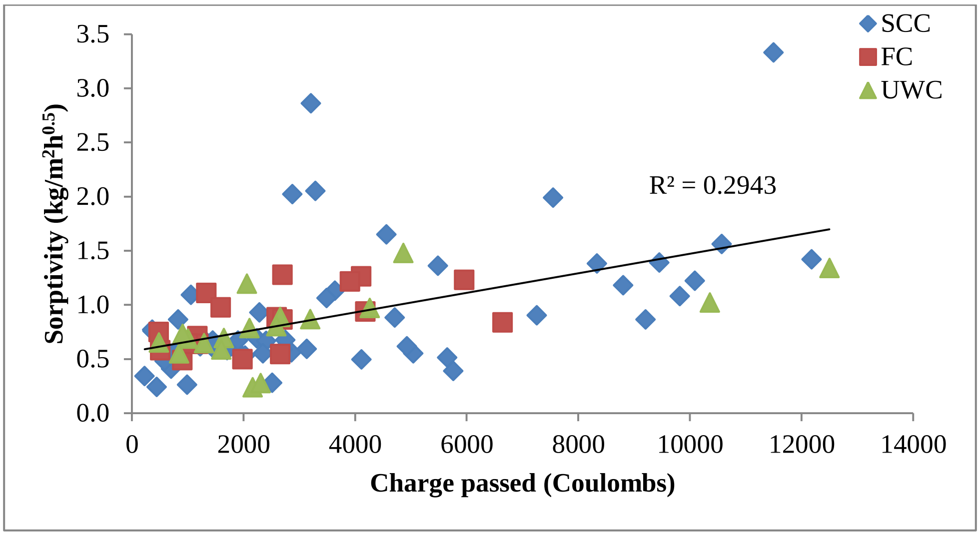


Figure 9-12 Relationship between sorptivity coefficient and total charge passed for SCC, FC and UWC

9.5 Embodied carbon content

This section focuses on the environmental aspect by evaluating and comparing the total embodied carbon content (ECO_2) of the concrete mixes. Many concrete users are interested in achieving a given strength, with a lesser interest in how this is achieved. Therefore the embodied carbon content per unit strength has also been calculated and the effect of age and additions on this are discussed. The total ECO_2 values were calculated by summing only the ECO_2 values of the powders and do not account for the ECO_2 content of the aggregates as for each concrete type the total aggregate content was kept constant.

9.5.1 Total embodied carbon content

As mentioned in Chapter 1, of the powders, Portland cement has the highest ECO_2 value of 913 kg/tonne followed limestone powder, ggbs and fly ash standing at 75, 67 and 4 kg/tonne respectively (MPA, 2010). Referring to Table 9-2, as expected the total ECO_2 decreases with increased replacement levels of additions as expected. These are illustrated in Figure 9-13.

For binary binder mixes, with a replacement level of 20%, the reductions in total ECO_2 with limestone powder and with ggbs in SCC was about 19% relative to the control mix as their ECO_2 are similar, whereas with fly ash the reduction was very slightly higher at 20%. However for higher replacement levels, 60 and 80%, the reductions with ggbs were about 56 and 75% respectively whereas with fly ash it was 60 and 80% respectively; i.e. a larger difference between the two at higher replacement levels. Having said that, it is important to view this reduction in ECO_2 on a larger scale, bearing in mind the fact that the annual world-wide concrete production is over 7 billion cubic meters (approximately one cubic meter of concrete per person). For instance, for 40% replacement in SCC, the total ECO_2 content of the mix with fly ash was 13 $kgCO_2/m^3$ lower than that of ggbs which, assuming, for example, that annually 1 million cubic meters of each of these SCC mixes was produced world-wide, the total ECO_2 content of the fly ash mixes would be 13 million $kgCO_2$ lower than that of ggbs mixes, which is significant. Also, due to the use of replacement by volume, the percentage reduction of total ECO_2 in FC and UWC are similar to those in SCC for the same replacement level of addition however the total ECO_2 content of FC and UWC control mixes (404 and 434 kg CO_2 respectively) were lower than that of SCC (475 kg CO_2) due to their lower Portland cement content.

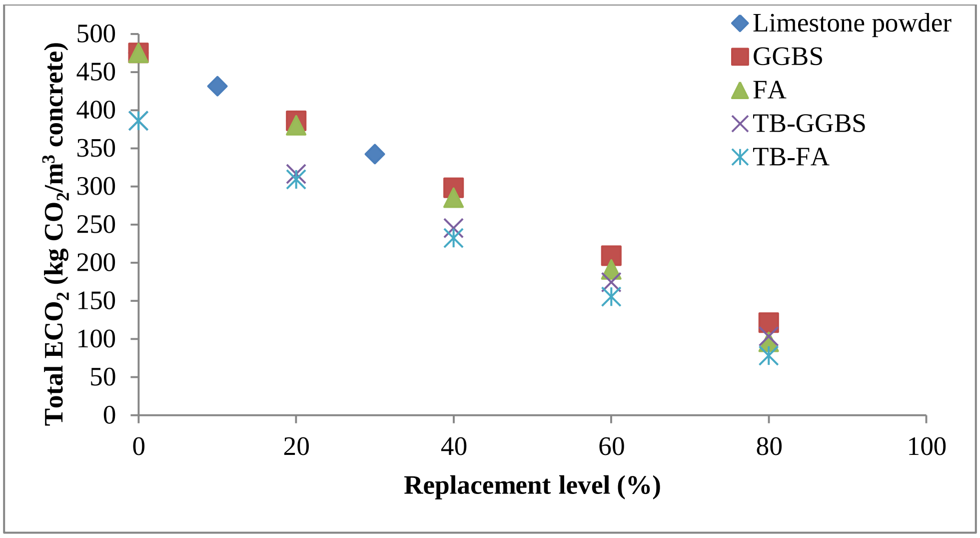


Figure 9-13 Total embodied carbon per m^3 concrete with different binder combinations

The ternary binder mixes had a lower total ECO_2 compared to their respective binary binder mixes as expected. Considering the mixes with 40% ggbs and with 20% fly ash, the binary binder mixes had reductions in ECO_2 of about 37 and 20% respectively whereas with the ternary binder mixes the reductions were about 48 and 35% respectively; an increase in reduction of around 11 and 15% respectively. The reason the increase in reduction is greater for the ternary binder mix with 20% fly ash is because the overall percentage of limestone powder in the mix is higher compared to that with 40% ggbs. For instance, for SCC mixes with 20, 40, 60 and 80% ggbs, the increase in ECO_2 reductions of ternary binder mixes were 15, 11, 7 and 4% respectively.

9.5.2 Embodied carbon content per unit strength

As the compressive strength increases with age, the embodied carbon/unit strength therefore decreases (Table 9-2). For binary binder SCC mixes with limestone powder, the embodied carbon/unit strength at 91 days decreases with increasing replacement levels and was lower than that of the control mix at all replacement levels. Similarly with ggbs, the embodied carbon/unit strength decreases with increasing replacement levels however, unlike limestone powder, the values, at all ages, were lower than that of the control mix; for mixes with 20 and 80% ggbs the values at 91 days were 5.25 and 2.51 kg CO_2/MPa respectively (Figure 9-14). This indicates that the relative reduction in ECO_2 content was greater than the reduction in compressive strength. For example the mix SCC-G40, having a lower total ECO_2 content, attained a similar 91-day strength to the control mix hence it has a lower embodied carbon/unit strength (4.26 compared to 6.77 kg CO_2/MPa). For fly ash mixes, the embodied carbon/unit strength at 91 days decreased up to 40% replacement but increased thereafter (Figure 9-14); the 80% fly ash mix had the highest value (6.72 kg CO_2/MPa) which was similar to that of the control mix due its very low compressive strength. Hence on this basis the SCC-F80 mix offers no advantage over the control mix as they have similar performance. Due to the decrease in early age strength with increased addition levels, the trend was slightly different at early ages; for instance for the fly ash mixes the embodied carbon/unit strength actually increased at 3 and 28 days with increasing replacement levels. Looking at the long-term values, all the binary binder SCC mixes had a lower embodied carbon/unit strength than that of the control mix.

For FC and UWC, unlike SCC, the mixes with 20% limestone powder had a higher embodied carbon/unit strength at 91 days compared to their respective control mixes. However, as with SCC, the mixes FC-G40 and UWC-G40 both had a lower 91-day embodied carbon/unit strength compared to their respective control mix. This was also the case for UWC-F20, but not for FC mix with fly ash (FC-F20) which had a higher embodied carbon/unit strength at 91 days compared to FC-C.

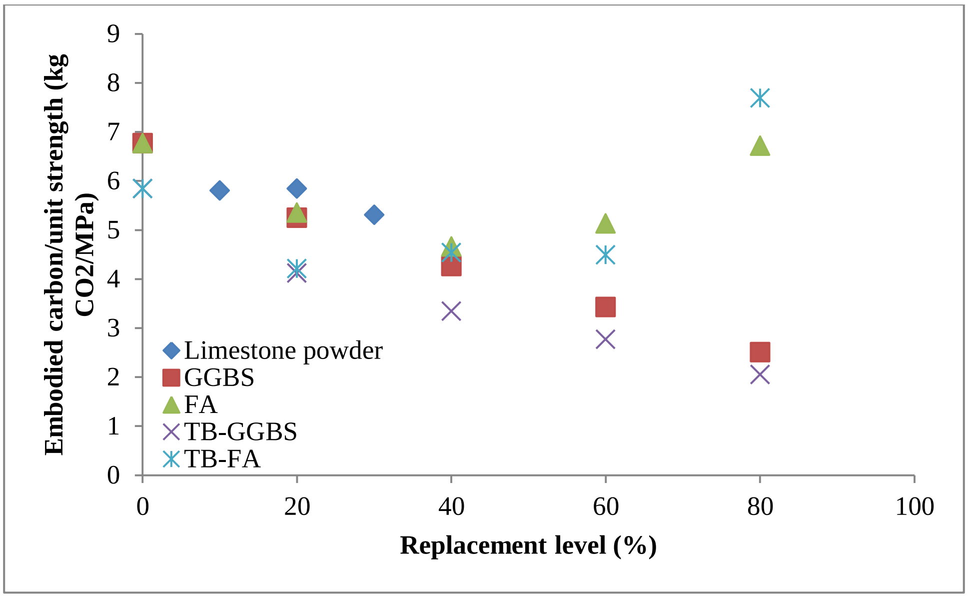


Figure 9-14 Embodied carbon per unit strength (91 days) for SCC with different binder combinations

The ternary binder SCC mixes had higher embodied carbon/unit strengths at 3 days than their respective binary binder mixes, which is due to the increased replacement level resulting in further reductions in early-age compressive strength. However the embodied carbon/unit strength of these mixes at 91 days was lower than the control mix and their respective binary binder mixes, with the exception of SCC-TB-F80 which had a higher value (Figure 9-13). This is an environmental advantage as for the same strength performance ternary binder mixes have lower ECO_2; it is also a potential economic advantage, depending on the availability and cost of materials, as mixes have a lower Portland cement content.

For FC and UWC, even though the ternary binder mixes were unable to attain similar strengths at 91 days to the binary binder mixes they still had lower embodied carbon/unit strengths than the binary binder mixes with the exception of UWC-TB-F20. Both ternary binder mixes with fly ash had similar values to their respective control mixes hence they do not offer any significant advantages in terms of embodied carbon/unit strength.

Table 9-2 Embodied carbon content for all mixes

Mix No.	**Mix Ref.**	**ECO_2 (kg CO_2/m^3 concrete)**	**ECO_2 / strength (kg CO_2/MPa)**			**Equivalent strength PC mix ECO_2 (kg CO_2/m^3 concrete)**	
			3	**28**	**91**	**28**	**91**
1	SCC-C	475	9.57	7.95	6.77		
2	SCC-L10	431	9.90	7.54	5.80		
3	SCC-L20	386	10.70	8.22	5.84	356	434
4	SCC-L30	342	11.49	6.91	5.31		
5	SCC-G20	386	8.88	6.50	5.25		
6	SCC-G40	298	9.21	4.75	4.26	457	457
7	SCC-G60	209	8.36	4.54	3.43		
8	SCC-G80	121	5.53	2.74	2.51		
9	SCC-F20	380	8.74	6.73	5.35	405	457
10	SCC-F40	285	9.54	5.68	4.66		
11	SCC-F60	191	15.63	6.81	5.13		
12	SCC-F80	96	26.70	12.65	6.72		
13	SCC-TB-G20	316	10.15	5.83	4.12		
14	SCC-TB-G40	245	9.41	4.51	3.34	405	469
15	SCC-TB-G60	174	7.83	3.53	2.77		
16	SCC-TB-G80	103	5.42	2.45	2.05		
17	SCC-TB-F20	309	9.26	4.72	4.21	469	469
18	SCC-TB-F40	232	12.70	5.56	4.54		
19	SCC-TB-F60	155	18.50	6.07	4.49		
20	SCC-TB-F80	78	37.36	11.71	7.69		
21	FC-C	404	10.10	7.23	6.13		
22	FC-L20	329	11.11	7.06	6.14	342	349
23	FC-G40	254	10.54	4.93	4.23	363	379
24	FC-F20	324	15.05	8.45	6.76	307	307
25	FC-TB-G40	208	11.33	4.88	4.14	324	336
26	FC-TB-F20	264	14.23	7.63	5.98	292	307
27	UWC-C	434	10.40	7.09	6.61		
28	UWC-L20	353	12.55	8.43	7.48	324	330
29	UWC-G40	272	12.66	6.15	4.82	336	356
30	UWC-F20	347	10.77	7.29	5.86	349	379
31	UWC-TB-G40	224	12.08	4.83	4.15	349	356
32	UWC-TB-F20	283	13.91	8.71	6.22	274	307

It is useful to assess the performance of mixes by comparing their ECO_2/unit strengths with those of a 100% PC mix with the same strength. These were obtained by:

- Obtaining the required water/cement ratio for the strength using the BRE mix design method.
- Calculating the PC content for an assumed water content of 195 kg/m^3. The BRE mix design method suggests this water content, for mixes made with uncrushed aggregates (maximum aggregate size of 20mm), to achieve slump values ranging from 60 – 180mm. As this water content was also used in FC mixes it was reasonable, for comparison purposes, to use the same value.
- Multiplying the PC content by its embodied carbon content i.e. 913 kgCO_2/tonne

The values obtained for the 28 and 91 day strengths of selected mixes are shown in the last two columns of Table 9-2.

The majority of the equivalent PC mixes have higher embodied carbon content than their corresponding mixes with additions at both ages with the exception of FC-F20 and UWC-L20. Two of the mixes, SCC-L20 and UWC-TB-F20, had a higher embodied carbon content compared to the equivalent PC mix at 28 days but a lower value at 91 days. Also the embodied carbon content was higher at 91 days compared to at 28 days; this is due to the increased strength gain in mixes with additions between 28 and 91 days from the secondary reactions resulting in the equivalent PC mix at 91 days having a lower water/cement ratio (Appendix 9). Hence it is preferable to use additions as a method of reducing the embodied carbon content of concrete rather than increasing the water/cement ratio i.e. reducing the PC content. The use of additions can not only improves the rate of long-term strength gain (after 28 days) but, as discussed in 9.4.1, also improves the durability of the concrete due to the formation of a denser microstructure.

Table 9-3 ECO_2 of equivalent strength mixes (for SCC) with different binder combinations

Strength	**PC**	**GGBS**	**FA**	**TB-GGBS**	**TB-FA**
60 MPa @ 28 days	control	40%	15%*	15%*	25%*
Total ECO_2 (kg CO_2/m^3 of concrete)	475	298	404	333	290
ECO_2/unit strength (kg CO_2/MPa)	7.92	4.96	6.73	5.55	4.84
70 MPa @ 91 days	control	40%	20%	45%*	25%*
Total ECO_2 (kg CO_2/m^3 of concrete)	475	298	380	227	290
ECO_2/unit strength (kg CO_2/MPa)	6.79	4.25	5.43	3.24	4.15

*estimated values

It is also possible to estimate the maximum replacement levels of each of the additions which would achieve similar 28 and 91-day strengths to those of the SCC control mix (i.e. 60 and 70 MPa respectively). The results are given in Table 9-3. For binary binder mixes with ggbs and fly ash, a maximum replacement level of 40 and 15-20% respectively would result in mixes achieving similar strengths as the control mix. For the ternary binder mixes, at 28 days, the maximum replacement level for ggbs reduced to 15% due to the slow early-age strength gain, however more interestingly, at 91 days, the maximum replacement levels for ggbs and fly ash are 5% higher than their corresponding binary binder mixes (excluding the fact that in ternary mixes one fifth of the primary binder is limestone powder). At 91 days, for both binary and ternary binder combinations, ggbs mixes perform better than fly ash mixes; achieving the same compressive strength with almost double the replacement level and therefore have a lower ECO_2/unit strength. Hence, with the exception of the ternary binder mix with ggbs at 28 days, it is possible to incorporate higher replacement levels in ternary binder mixes whilst maintaining the required strength at 28 and 91 days. This results in a lower total ECO_2 and therefore a lower embodied carbon per unit strength which is clearly advantageous.

9.6 Conclusions

After the combined analysis the entire set of test results, it was found that:

1. There is a good relationship between the slump and slump flow values and also between the flow table values and slump flow. These fit well with similar results from the literature.

2. The strength reduction at early ages, for the same addition level, is greater for FC and UWC compared to SCC. In the long-term, SCC mixes with up to 40% ggbs and one with 20% fly ash achieved similar or higher 91-day strengths to the control, however this was not the case with FC and UWC mixes. In other words, the negative impact of additions on the strength is less in SCC than in FC and UWC, this could be attributed to its lower water/cement ratio.

   Ternary binder SCC mixes with up to 40% ggbs and 20% fly ash achieved similar or greater strengths at 91 days than their respective binary binder mixes, however, as with the binary binder mixes, this was not the case with FC and UWC. Hence it is possible to use ternary binders in SCC without affecting the long-term strength but with potential economic and environmental advantages.

3. There was a good relationship between compressive strength and tensile splitting strength, UPV and dynamic elastic modulus for all three concrete types.

4. There was also a good relationship between the sorptivity coefficients and the compressive strength but surprisingly there was no noticeable difference in the sorptivity values for the different concrete types. For compressive strength values ranging from 25 to 65MPa, the sorptivity values ranged from 1.5 to 0.25 $kg/m^2h^{0.5}$ for all mixes.

5. The results from the rapid chloride penetration test had a large scatter with no clear effect of the different binder compositions or of the different concrete types; however the degree of scatter was lower for higher strength mixes.

   From these results, the author believes that this test is not suitable as a durability indicator when comparing mixes with different binder compositions; however it may be used, with caution and under laboratory conditions, to compare mixes with different replacement levels of the same addition level or to check production consistency of a mix with the same binder composition.

6. The use of additions reduces the total embodied carbon content of the mixes, as expected. The majority of the binary binder mixes had lower embodied carbon/unit strength at 91 days, indicating that the reduction in the embodied carbon is greater than the reduction in strength.

   The ternary binder mixes had higher embodied carbon/unit strength at early ages compared to their relative binary binder mix due to the reduction in early-age strength. For SCC ternary binder mixes, the embodied carbon/unit strength at 91 days was lower than the respective binary binder mixes. For FC and UWC, even though the ternary binder mixes had lower strengths, they had similar embodied carbon/unit strength as their respective binary binder mixes and so, unlike SCC, do not offer any significant advantages in terms of embodied carbon/unit strength.

   The majority of the equivalent PC mixes had a higher embodied carbon content than the corresponding mix containing additions, which demonstrates that it is advantageous to use additions as a method of reducing the PC content rather than by using a higher water/cement ratio.

   For equivalent strength SCC mixes, at 91 days, the addition level of fly ash and ggbs is 5% higher for ternary binder mixes than the corresponding binary binder mixes which again can have potential economic and environmental advantages.

Chapter 10 Conclusions and Future Work

This research looked at the effects of different binder compositions (binary and ternary) on the properties of three types of high-consistence concrete (SCC, FC and UWC). The work began by selecting typical fresh target properties and mix design procedures for each type of concrete and then producing control Portland cement based mixes with these properties. This was followed by examining mixes with binary and ternary binder compositions consisting of:

- **Binary binders:** Up to 80% replacement of Portland cement with fly ash or ggbs and up to 30% replacement with limestone powder with mixes adjusted to have the target fresh properties. All replacements were by volume.

- **Ternary binders:** Using a base binder of Portland cement: limestone powder in ratio of 4:1, replacing up to 80% of that with ggbs or fly ash, again with mixes adjusted to have the target fresh properties. All replacements were by volume.

Various tests were carried out to determine the hardened mechanical and durability properties of the resulting concrete mixes at ages of up to 91 days. The relationships between the hardened properties were investigated and the embodied carbon content of the concrete mixes were evaluated and compared.

This chapter presents the main conclusions drawn from this research and gives some recommendations for future work.

10.1 Conclusions

10.1.1 Fresh properties

- High-consistence concrete can be successfully produced with both binary and ternary binder combinations. In this project high-consistence concrete mixes were successfully produced with up to 80% replacement of ggbs or fly ash and limestone powder up to 30% replacement by volume (binary binder). Similarly ternary binder mixes were successfully produced, with a base binder of Portland-limestone cement (4:1 ratio), with up to 80% ggbs or fly ash replacement. The admixture dosages were adjusted to ensure mixes achieved the target fresh properties.

- All three additions increased the consistence, irrespective of concrete type, so the superplasticiser dosage was reduced to achieve the target consistence. Ternary binder mixes required a slightly lower admixture dosage.

  For example, the SCC mix with 40% ggbs replacement required a superplasticiser dosage of 1.1% by weight of powder compared to 1.5% for the control mix whereas the ternary binder mix with the same replacement level required a dosage of only 1%.

- For stability, all the SCC mixes with the exception of SCC-F40 required the incorporation of a VMA to control segregation and similarly UWC required an AWA to control the washout resistance. The incorporation of additions resulted in reduced mix stability therefore an increase in VMA and AWA dosage was required. Mixes with fly ash were least stable and those with limestone powder were most stable hence the former required a higher dosage of VMA and AWA to achieve adequate stability and vice versa. Also higher replacement levels resulted in a less stable mix. Ternary binder mixes were less stable than their corresponding binary binder mixes hence required a higher dosage for stability.

For example, SCC mix with 40% ggbs required a VMA dosage of 0.1% compared to no VMA for the control mix whereas the corresponding ternary binder mix required double the dosage i.e. 0.2%.

For UWC with 40% ggbs, both the binary and ternary binder mixes required a slightly higher AWA dosage of 0.6% compared to 0.5% for the control mix. It must be noted that the superplasticiser dosage also has an effect on the required VMA and AWA dosage. For example, an increase in the superplasticiser dosage of any of these mixes would results in a less stable mix hence a higher VMA or AWA dosage would be required.

- Good correlations exist between the V-funnel time and plastic viscosity for SCC mortar and concrete mixes, confirming previous relationships. Good correlation also exists between the slump flow and yield stress values (from literature) however in this work the range of these values were not sufficiently wide to obtain a meaningful correlation. Also the relationship between slump-slump flow and flow table-slump flow fall within the range of results given in the literature.

10.1.2 Strength

- The incorporation of additions led to reductions in the concrete strength as expected. The reductions were higher at higher replacement levels at early age, but reduced with increasing age.

For example, the SCC mix with 40% ggbs had a 50% strength reduction at 1 day compared with the control mix whereas it had a similar strength at 91 days. Increasing the replacement level to 80% resulted in a higher strength reduction at 1 day of 83% whereas at 91 days the strength reduction was only 32%. The strength reductions with fly ash were similar to ggbs up to 40% replacement but significantly higher at 60 and 80% replacement which is simply due to the different chemical nature of these two additions; the strength reduction for SCC mix with 80% fly ash was 95% at 1 day and 80% at 91 days.

From previous studies, it was anticipated that the incorporation of limestone powder may increase the rate of initial hydration resulting in a higher early strength, however this benefit was not seen. This could be due to the fact that the lowest limestone powder replacement of 10% was too high for this effect.

- Optimum replacement of fly ash and ggbs in SCC were found to be 20 and 40% respectively; that is the highest replacement level at which mixes attained a similar long-term (91-day) strength to the control mix. However, for the same replacement levels, for both FC and UWC, the mixes had lower 91-day strength compared to the control mix. This could be attributed to the lower water/cement ratio of SCC having a higher rate of hydration reaction further promoting the secondary reactions resulting in a higher strength gain.

- The early-age strength reduction was greater in ternary binder compared to binary binder mixes, as expected, since the Portland cement replacement is higher hence the initial hydration is slower. As with the binary binder mixes, the incorporation of limestone powder did not show any benefits in increasing the early-age strengths. However ternary binder SCC mixes with optimum replacement levels of fly ash and ggbs attained higher long-term strengths (3-5 MPa) compared to their respective binary binder mixes. This shows that there exists some synergistic effect between ggbs and fly ash with limestone powder. It could be that the presence of limestone powder, due to it being finer that the other powders resulted in increased available surface area for hydrates to be formed leading to higher rate of secondary reactions resulting in higher long-term strength.

- For FC and UWC, however, the ternary binder mixes, attained lower strengths compared to both their respective binary binder mixes and the control mix. Again this could be due to their higher water/cement ratio than the SCC, hence it is reasonable to conclude that the use ternary binders in SCC or mixes with low water/cement ratio (<0.4) is possible without hindering the long-term strength but with potential economic and environmental advantages such as reduction in the embodied carbon of concrete.

- Good correlation was found between tremie and air cast UWC cubes. Compressive strength ratio of tremie/air was about 0.8 as reported in the literature.

- Also, for all concrete, good correlation exists between the compressive strength and the tensile splitting strength, UPV and dynamic elastic modulus with most values within the range given by Eurocode 2 (EC2) and CEB FIB Model 1990 design codes.

10.1.3 Durability

- GGBS replacement of up to 80% had negligible effect on SCC sorptivity. Fly ash replacement up to 40% also attained similar sorptivity to the control mix with 60 and 80% replacement having higher sorptivity values. For FC and UWC fly ash (20%) and ggbs (40%) mixes both attained similar sorptivity coefficients at 7 and 28 days but, surprisingly, higher values at 91 days compared to the control mix.

- For ternary binder SCC, early-age sorptivity (7-day) was higher than that for the binary binder mix due to presence of limestone powder but similar or lower sorptivity values at 91 days were attained by all mixes.

For both FC and UWC, the inclusion of limestone powder in ternary binder mixes resulted in higher sorptivity coefficients than the respective binary binder mixes at both 7 and 91 days. Hence unlike with the strength of SCC, no synergistic or positive effects were noticed with using ternary binder combination.

In general, the sorptivity coefficients of FC and UWC mixes were higher than SCC which again could be attributed to their higher water/cement ratio. Good correlation exists between the sorptivity coefficients and the compressive strength but surprisingly, for a given strength, there was no noticeable difference in the sorptivity values for the different types of concrete. The sorptivity values ranged from 1.5 to 0.25 $kg/m^2h^{0.5}$ for compressive strength ranging from 25 to 65 MPa for all mixes.

- The rapid chloride penetration test results had a high degree of scatter. No clear effect of the different binder compositions or the different concrete types was seen nor was there any correlation with compressive strength or sorptivity results as was initially expected. This could be due to the fact that the result of this test is very much influenced by the chemistry of the pore solution.

  The author therefore believes that this test is not suitable for use as a durability indicator when comparing concrete mixes with different types of additions because the mixes would have different pore chemistry. Having said that, this test may be used, with caution and under laboratory conditions, for comparing concrete with different levels of the same addition or as a quality control tool checking the production consistency of one specific mix.

10.1.4 Embodied carbon

- The majority of the binary binder mixes had lower embodied carbon/unit strength at 91 days, indicating that the reduction in the embodied carbon is greater than the reduction in strength.

  Ternary binder mixes had higher embodied carbon/unit strength at early ages compared to their relative binary binder mix due to the reduction in early-age strength. For SCC, the embodied carbon/unit strength at 91 days was lower than the respective binary binder mixes. For FC and UWC, even though the mixes had lower strengths, they had similar embodied carbon/unit strength to their respective binary binder mixes and so, unlike SCC, do not offer any significant advantages in terms of embodied carbon/unit strength.

  Equivalent strength PC mixes had a higher embodied carbon content than the equivalent mix with additions indicating the advantage of using additions as a method of reducing the PC content. Also for equivalent strength SCC mixes, at 91 days, ternary binder mixes have a 5% higher replacement level of ggbs and fly ash relative to the binary binder mixes which again can have potential economic and environmental advantages.

10.1.5 Overall summary

This project looked at the feasibility of using ternary binder blends of Portland-limestone cement (4:1 ratio) with ggbs or fly ash (PLC/GGBS or PLC/FA) for high-consistence concrete i.e. SCC, FC and UWC. This section gives an overall summary of the findings.

- ➢ **Fresh properties:** It is feasible to produce high-consistence concrete, having similar fresh properties, with ternary blended binders (PLC/GGBS or PLC/FA) with minimal adjustments to the admixture dosages relative to that of binary blended binders i.e. PC/GGBS or PC/FA. In the case of SCC and UWC, it was found that with ternary binder mixes a lower superplasticiser dosage was needed but in addition a small dosage of a stabilising admixture was also needed resulting in similar overall admixture dosages (superplasticiser + stabiliser (if any)) between the binary and ternary binder mixes.

- **Strength:** It is possible to achieve similar or higher long-term compressive strengths with ternary binder mixes (with ggbs and fly replacements of up to 40 and 20% respectively) relative to binary binder mixes for concrete with low water/cement ratio (<0.4). Hence there exists some synergistic effect between the limestone powder and ggbs and fly ash. This benefit was only seen with SCC mixes (w/c 0.32) and not with FC and UWC mixes (w/c 0.44). Ternary blended binders have less Portland cement which in itself can have potential economic and environmental advantages by reducing the total embodied carbon of the concrete.

- **Durability:** It is possible to produce ternary binder mixes, with low water/cement ratio (<0.4), having similar or lower sorptivity coefficients. As with strength, this benefit was only noticed with SCC mixes and not with FC and UWC mixes.

  Embodied carbon: It is possible to achieve lower embodied carbon/unit strength values with ternary binder concrete mixes having a low water/cement ratio (<0.4) which indicates that the reduction in embodied carbon is greater than the reduction in strength.

10.2 Recommendations for Future Work

The higher powder content in high-consistence concrete compared to normal-consistence concrete provides an opportunity to replace the Portland cement with different types of and higher levels of additions which can have potential economic advantages and environmental advantages. The results from this research indicate that, when used in combination, there exists some synergistic effect between limestone powder and ggbs and fly ash especially for SCC or mixes with low water/cement ratio (<0.4). Hence further research is valuable and the following areas of study are recommended:

- Significant work has been done looking at the effect of particle packing in cement and concrete and a number of software products have been developed over the years with one such software being EMMA. These can help obtain the optimum packing of any combination of materials given the particles size distributions of the individual materials. One of the main advantages of limestone powder is it being finer than Portland cement hence achieving the optimum packing (not necessarily the densest packing) would allow the utmost benefit from its use. Hence for binder combinations with limestone powder, greater use of such software products would be beneficial for obtaining the optimum packing and these could be further developed to be able to estimate, given some initial test results with the different powders, influence on the hardened properties of concrete.

- Investigation of the durability properties of ternary binder systems with limestone powder. In the current study, sorptivity and the rapid chloride penetration tests were performed, however, it is necessary to consider other aspects of the durability of ternary binder systems including assessment of long-term chloride penetration as the accelerated tests performed in this work were inconclusive.

- There is a good correlation between sorptivity and compressive strength however there is a lack of data looking at the correlation between sorptivity and other durability aspects of concrete which could lead to durability classifications for sorptivity.

- This research has shown that it is possible to use ternary binder combinations of well-known additions such as limestone powder, fly ash and ggbs in high-consistence concrete and achieve a mix with similar or better performance in both strength and durability that the binary binder mix using a lower Portland cement content. There is scope for further investigating this synergistic effect between limestone powder and ggbs and fly ash to further reduce the Portland cement content leading to greater potential economic and environmental advantages.

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Appendix 1 Diagrams and Dimensions of Test Apparatus

A1. 1 Self-compacting Concrete

- **Slump flow test**

Refer to Figure 4-8 in Chapter 4.

- **V-funnel test**

Refer to Figure 4-9 in Chapter 4.

- **J-ring test**

Refer to Figure 4-10 in Chapter 4.

- **Sieve segregation test**

Refer to Figure 4-11 in Chapter 4.

- **L-box test**

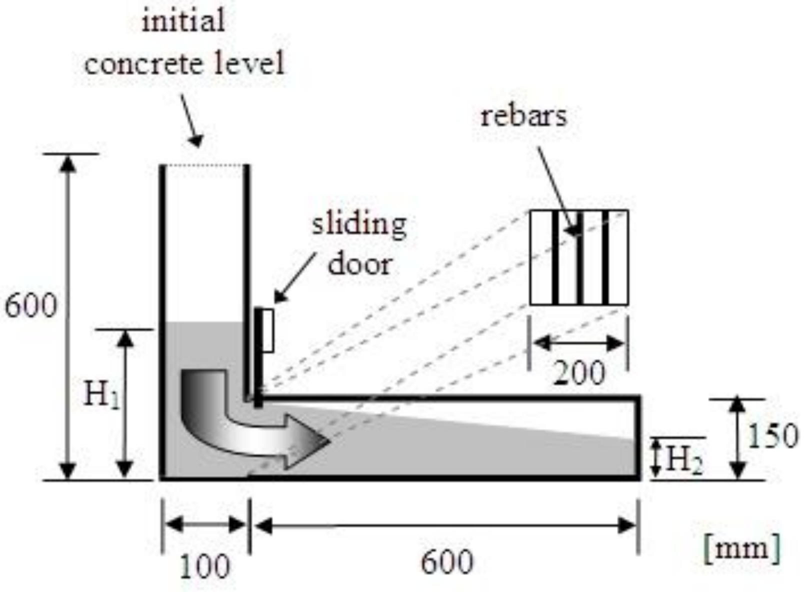


Figure A1-1 Schematic of L-box test

A1. 2 Flowing concrete

- **Conventional slump test**

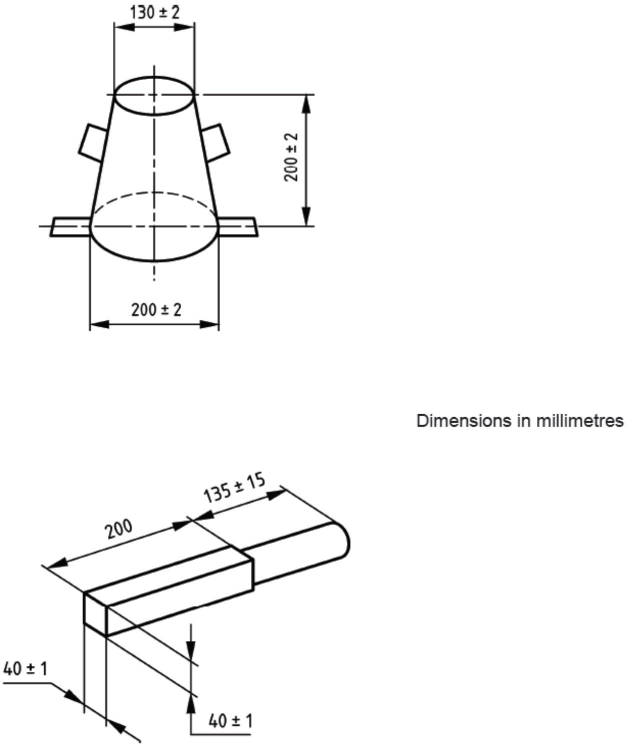
Refer to Figure 4-8 in Chapter 4. Similar apparatus as slump flow test.

Appendix 1 Diagrams and Dimensions of Test Apparatus

- **Flow table test**

board dimension 700x700mm

(a)



(b)

Figure A1-2 Schematic of Flow table test

A1. 3 Underwater concrete

- Plunge test

Refer to Figure 4-13 in Chapter 4.

- Stream test

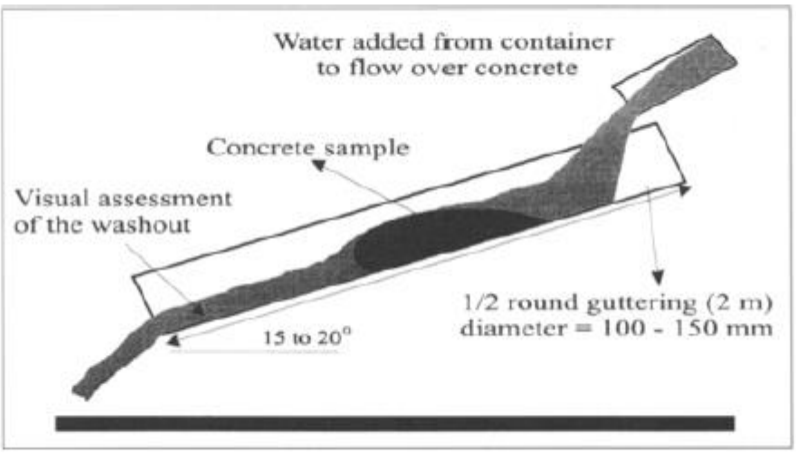


Figure A1-3 Schematic of stream test (Sonebi et al., 1999)

Appendix 2 Minutes of Meetings with Industry

A2. 1 Alan Bromwich (Lafarge aggregates)

Date: 25th February 2009

Purpose: Discussion about possible research areas/topics that could be undertaken within concrete technology

Meeting with: **Alan Bromwich**
Technical Manager
E-mail: alan.bromwich@lafarge-ukaggregates.lafarge.com

Address:
Lafarge Aggregates
Central Lab
Gibbet Lane
Shawell
Leicester
LE17 6AA

Below are few points/comments made by Alan Bromwich during the meeting:

- Work on PFA and GGBS has intensively been done. Presently concrete with replacements of up to 50 – 60% and up to 90% of PFA and GGBS respectively have been used in industry. (Alan would be able to provide job references where concrete with these high amounts of replacements has been used).
- ASR would be a problem when using ground glass. He also mentioned that not much ground glass is gone to waste in the present time, they are re-used

in road constructions and other types of fill, so when doing research on ground glass we have to consider whether it would be more beneficial leaving the ground glass being used in road construction or to use it in concrete? For example if using ground glass in concrete would result in increasing the powder content then it would not be beneficial since the cost is increased.

- Consider also researching the use of recycled coarse aggregate (20mm, 10mm …) in concrete rather than concentrating only on fine materials. (Lafarge Aggregates produce recycled aggregates, hence Alan he could give us a contact within their recycled aggregates department who would be able to supply us with samples of their aggregates).

- The advantages of SCC are measured in terms of man-hours saved which would be converted in a quantity of money, helping us to compare the price of SCC with NVC.

- He mentioned that he would be happy to hold site/lab tours if I would be interested, showing me the production and use of their SCC (Agilia).

- In terms of admixtures, he recommended looking at BASF along with Sika and Grace. He would be glad for me to consult with him when choosing the best admixture for SCC since he was in the admixture business before joining Lafarge Aggregates.

- About their own SCC (Agilia), they could not reveal much about it since it is the leader in the market, however he did mention that they do not use VMA’s in their concrete, and use the Oval test rather than the V-funnel test (which they need to calibrate the two at some point in time)

A2. 2 Adrian Ashby (Hanson cement)

Date: 11th March 2009

Purpose: Discussion about possible research areas/topics that could be undertaken within concrete technology

Meeting with: **Adrian Ashby**
Technical Development Manager
E-mail: Adrian.Ashby@hanson.biz

Address: Hanson Cement
Ketton
Stamford
Lincolnshire
PE9 3SX

Below are few points/comments discussed during the meeting:

- Adrian Ashby was with Civil and Marine which has now merged with Castle Cement and Hanson Cement and the merged company is known as Hanson Cement. He is responsible for all powder products (hsc, pc, pfa, ggbs, etc…), however having been with Civil and Marine, his main interest still lies with ggbs.

- He mentioned that they get their clinker from multiple sources and the ggbs they produce varies in fineness (variation in SSA). The issue he mentioned was that the plants that use the materials to make CEM III cement are neither informed about the change in source of clinker nor about the change in ggbs SSA.

- The change in source of clinker and varying fineness of ggbs has an effect on the concrete performance and on the particle packing factor assuming the percentage replacement is kept constant.

- He also mentioned that even if al single source properties of all the materials are known, when blended, the properties could be different to what you initially expected.

- The main question to be answered is how can we assume consistent concrete performance with these variations in source of clinker and fineness of ggbs? In other words, can we produce a set of results from which the % replacement can to obtained for a clinker from a certain source with a ggbs of a certain fineness required to meet certain performance target?

- Data is available on the materials, namely particle size distribution (PSD). Tests should be done for different types of applications.

Below is a sample table of results, one way in which the results could be produced.

		Clinker Source								
		A	B	C	D	E	F	G		
GGBS Fineness (SSA)	400				65%				U	Performance Levels (should be defined)
	410								V	
	420			50%				-	W	
	430	60%					-	-	X	
	440	55%				-	-	-	Y	
	450	50%			-	-	-	-	Z	

Table showing % replacement of ggbs

- Then he showed a sample Asphalt Plant Dust (APD). This is obtained from the blacktop plant. In order for them to use less bitumen in the mix, they remove out very fine particles (95% passing 50 microns). The material has a known variable chemistry. Limestone, granite and quartz (from known sources) are the three main materials and the APD can be a combination of all three (or sometimes only 2) in different proportions. Very costly to separate out the three components. APD is an inert material.

- Here the main question is can test be done to understand the significance of the variable chemistry within APD and to somehow model the performance of the concrete? (for example maybe at low replacement levels, the variable chemistry can be neglected)

Other points discussed were:

- Tiocem (Titanium dioxide) is a type of cement that removes NOx from the atmosphere.
- Powdered day glass can be used with ggbs, reducing the risk of ASR.
- Using waste powder in concrete can reduce the cost and add to the sustainability.
- Search for an alternative activating agent (alternative binder to pc).

A2. 3 Darrell Newport (University of East London)

Date: 23rd March 2009

Purpose: Discussion about possible research areas/topics that could be undertaken within concrete technology

Meeting with: **Darrell Newport**
Director of the Sustainability Research Institute
E-mail: D.J.Newport@uel.ac.uk

Address: Room KD 2.21
Sustainability Research Institute
University of East London
4-6 University Way, Docklands
London
E16 2RD

Below are few points/comments discussed during the meeting:

- Production of lightweight aggregate by blending different proportions of waste together. These aggregates could be used to produce low-medium strength concrete. However they can produce aggregates to give concrete strengths up to 40 – 50 MPa.

- Also the use of waste from energy production was discussed. For example biomass produces ash which could be used in concrete keeping in mind that the ash would be organic.

A2. 4 Bryan Marsh (Arup)

Date: 23rd March 2009

Purpose: Discussion about possible research areas/topics that could be undertaken within concrete technology

Meeting with: **Bryan Marsh**
Materials Consulting
E-mail: bryan.marsh@arup.com

Address: Arup Materials
13 Fitzroy Street
London
W1T 4BQ

Below are few points/comments discussed during the meeting:

- Issues to address when looking at aggregate sourcing (location, quantity, chemistry etc…).
- The use of Rocktron fly ash in concrete
- Looking at triple blend mixes of PC-LF with pfa or ggbs, and analysing all the properties of the concrete. Dr Marsh believes that future cement production will contain 15 – 20 % limestone filler, hence understanding the properties of this cement when blended with pfa or ggbs is crucial.

A2. 5 Lindon Sear (UK Quality Ash Association)

Date: 1st April 2009

Purpose: Discussion about possible research areas/topics that could be undertaken within concrete technology

Meeting with: **Lindon Sear**
Technical director
E-mail: lkasear@ukqaa.org.uk

Address: UK Quality Ash Association
Maple House
Kingswood Business Park
Holyhead Road
Albrighton
Wolverhampton
WV7 3AU

Below are few points/comments discussed during the meeting:

- The types of ash that is available. i.e. high carbon (not very fine) fly ash and normal fly ash.
- Incinerator bottom ash has aluminium in it which causes expansion within concrete.
- He mentioned that it is very important to explain both the physical and the chemical reason when analysing and comparing different concrete mixes (many do not especially the chemical reason).
- Ken Day from Australia has written many papers on particle packing and has also developed a software product.

A2. 6 Mark Tyrer (Minerals Industry Research Organisation)

Date: 3rd April 2009

Purpose: Discussion about possible research areas/topics that could be undertaken within concrete technology

Meeting with: **Mark Tyrer**
Independent Geochemist
E-mail: mark.tyrer@miro.co.uk

Address: Minerals Industry Research Organisation
Concorde House
Trinity Park
Solihull
Birmingham
B37 7UQ

Below are few points/comments discussed during the meeting:

- The types of waste available to use in concrete. Looking at quarry fines, ferrosilicate slags, wheat straw ash, concrete crusher dust and steel slags.

Appendix 3 Principles of Heat of Hydration Method

It is assumed that the calorimeter is at constant temperature throughout with the temperatures of the sample pot and the heat sink being T_i and T_o respectively. Now the development of heat (dW) in the system over a short period of time (dt) raises the temperature of the sample pot above that of the heat sink by an amount T, hence:

$T = T_i - T_o$ (Equation A3-1)

Assuming the thermal capacity of the small pot is u then the internal heat absorption rate is

$u(dT/dt)$

The remainder of the heat leaks by conduction (not by convention or radiation) hence the rate of heat loss is proportional to T with constant coefficient p.

Rate of heat loss = pT (Equation A3-2)

Therefore balancing the heat release we get

$dW/dt = pT + u(dT/dt)$ (Equation A3-3)

The thermal electromotive force (EMF) which is the potential difference resulting from the change in temperature is proportional to this temperature difference T i.e.

$E = gT$ (Equation A3-4)

Substituting for T in the heat balance equation we get

$$dW/dt = pE/g + u(dE/dt)/g \qquad \text{(Equation A3-5)}$$

This can be rewritten as

$$dW/dt = K_1E + K_2(dE/dt) \qquad \text{(Equation A3-6)}$$

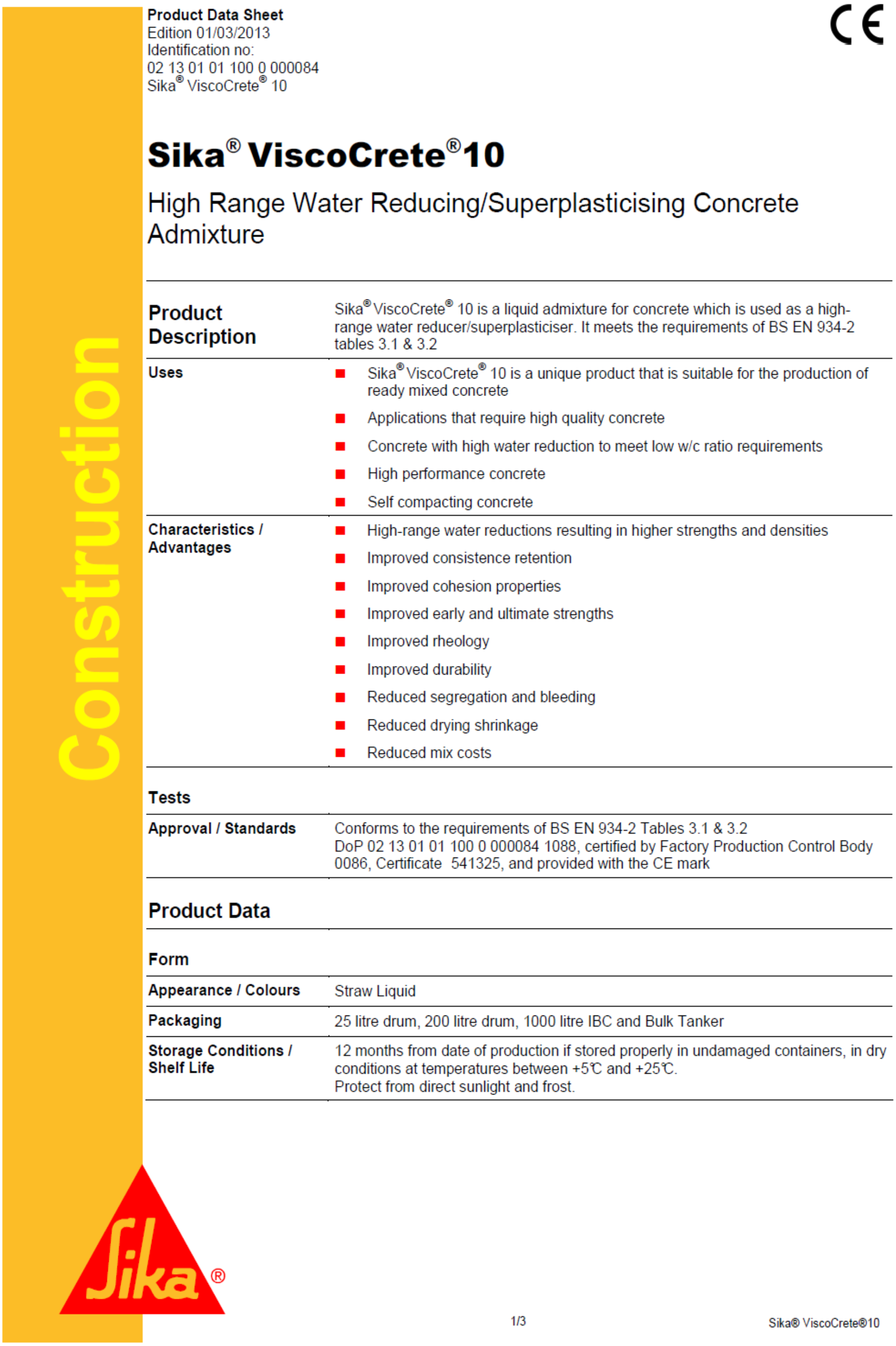
The above equation is known as the Tian-Calvet equation where K_1 and K_2 are constants for the calorimeter. The above equation can be rewritten as:

$$dE/dt = (-K_1/K_2)E + (dW/dt)/K_2 \qquad \text{(Equation A3-7)}$$

The values of the constants can be obtained by plotting a linear graph of dE/dt and E which is the calibration curve. This can be done by providing a constant supply of heat to the sample and measure the voltage response. Having the constants, the Tian-Calvet equation can then be used to convert the electrical impulses (millivolts) into heat output (W/kg).

Appendix 4 Admixture Data Sheets

A4. 1 Sika ViscoCrete 10



Product Data Sheet
Edition 01/03/2013
Identification no:
02 13 01 01 100 0 000084
Sika® ViscoCrete® 10

Construction

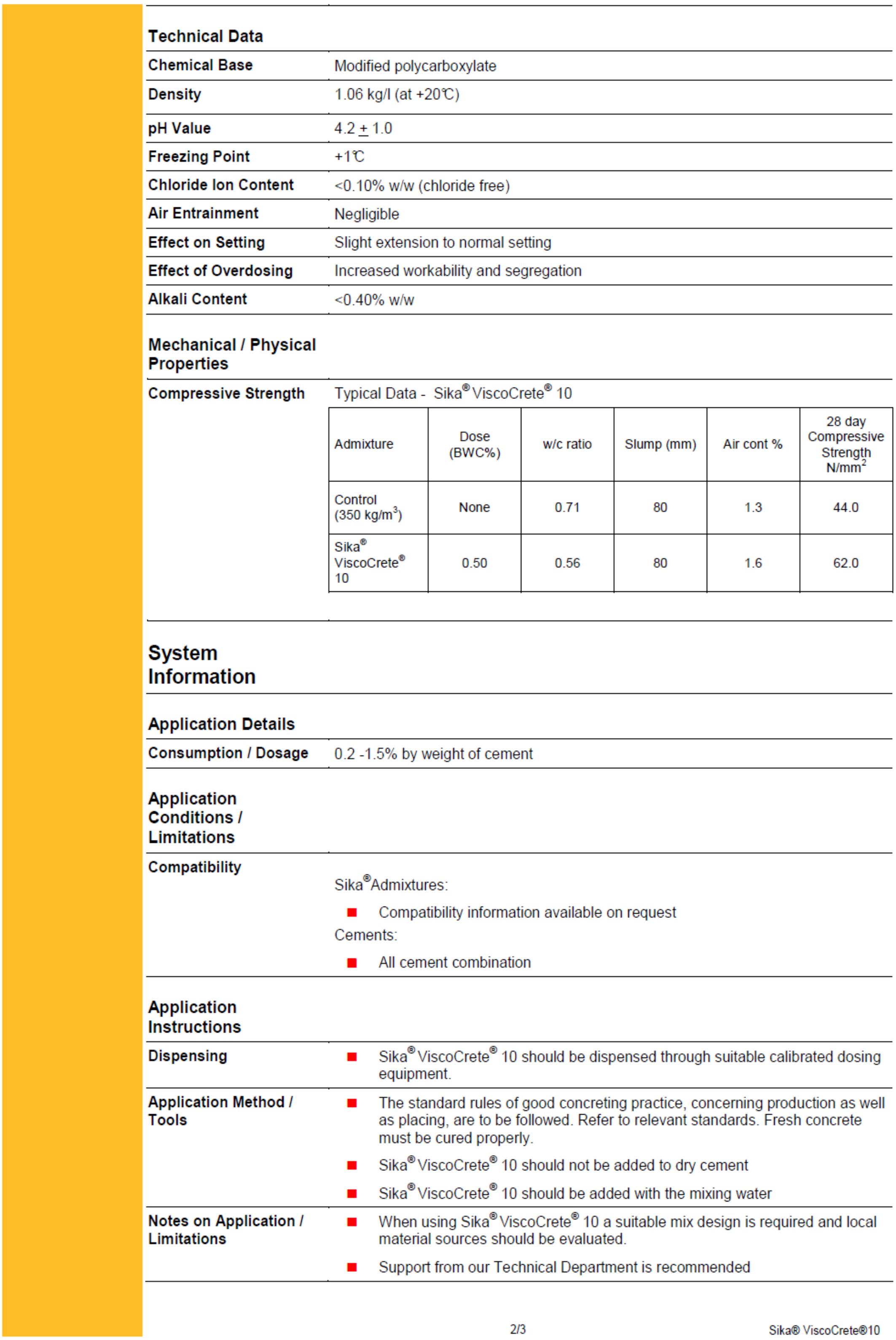
Sika® ViscoCrete®10

High Range Water Reducing/Superplasticising Concrete Admixture

Product Description	Sika® ViscoCrete® 10 is a liquid admixture for concrete which is used as a high-range water reducer/superplasticiser. It meets the requirements of BS EN 934-2 tables 3.1 & 3.2
Uses	■ Sika® ViscoCrete® 10 is a unique product that is suitable for the production of ready mixed concrete ■ Applications that require high quality concrete ■ Concrete with high water reduction to meet low w/c ratio requirements ■ High performance concrete ■ Self compacting concrete
Characteristics / Advantages	■ High-range water reductions resulting in higher strengths and densities ■ Improved consistence retention ■ Improved cohesion properties ■ Improved early and ultimate strengths ■ Improved rheology ■ Improved durability ■ Reduced segregation and bleeding ■ Reduced drying shrinkage ■ Reduced mix costs
Tests	
Approval / Standards	Conforms to the requirements of BS EN 934-2 Tables 3.1 & 3.2 DoP 02 13 01 01 100 0 000084 1088, certified by Factory Production Control Body 0086, Certificate 541325, and provided with the CE mark
Product Data	
Form	
Appearance / Colours	Straw Liquid
Packaging	25 litre drum, 200 litre drum, 1000 litre IBC and Bulk Tanker
Storage Conditions / Shelf Life	12 months from date of production if stored properly in undamaged containers, in dry conditions at temperatures between +5°C and +25°C. Protect from direct sunlight and frost.

1/3

Sika® ViscoCrete®10



Technical Data

Chemical Base	Modified polycarboxylate
Density	1.06 kg/l (at +20℃)
pH Value	4.2 ± 1.0
Freezing Point	+1℃
Chloride Ion Content	<0.10% w/w (chloride free)
Air Entrainment	Negligible
Effect on Setting	Slight extension to normal setting
Effect of Overdosing	Increased workability and segregation
Alkali Content	<0.40% w/w

Mechanical / Physical Properties

Compressive Strength

Typical Data - Sika® ViscoCrete® 10

Admixture	Dose (BWC%)	w/c ratio	Slump (mm)	Air cont %	28 day Compressive Strength N/mm^2
Control (350 kg/m^3)	None	0.71	80	1.3	44.0
Sika® ViscoCrete® 10	0.50	0.56	80	1.6	62.0

System Information

Application Details

Consumption / Dosage 0.2 -1.5% by weight of cement

Application Conditions / Limitations

Compatibility

Sika® Admixtures:

- Compatibility information available on request

Cements:

- All cement combination

Application Instructions

Dispensing

- Sika® ViscoCrete® 10 should be dispensed through suitable calibrated dosing equipment.

Application Method / Tools

- The standard rules of good concreting practice, concerning production as well as placing, are to be followed. Refer to relevant standards. Fresh concrete must be cured properly.
- Sika® ViscoCrete® 10 should not be added to dry cement
- Sika® ViscoCrete® 10 should be added with the mixing water

Notes on Application / Limitations

- When using Sika® ViscoCrete® 10 a suitable mix design is required and local material sources should be evaluated.
- Support from our Technical Department is recommended

Construction

Value Base	All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.
Local Restrictions	Please note that as a result of specific local regulations the performance of this product may vary from country to country. Please consult the local Product Data Sheet for the exact description of the application fields.
Health and Safety Information	For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.
Legal Notes	The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.
CE Labelling	EN 934-2:2009 is a candidate "harmonized" European Standard and fully takes into account the requirements of the European Commission mandate M128. Products related to concrete, mortar and grout, given under the EU Construction Products Directive (89/106/EEC) and intended to lead to CE marking. CE-labelled as per Annex ZA.3, table ZA.2 conformity 2+ and fulfil the requirements of the given mandate of the EU Construction Products Directive (89/106/CE).

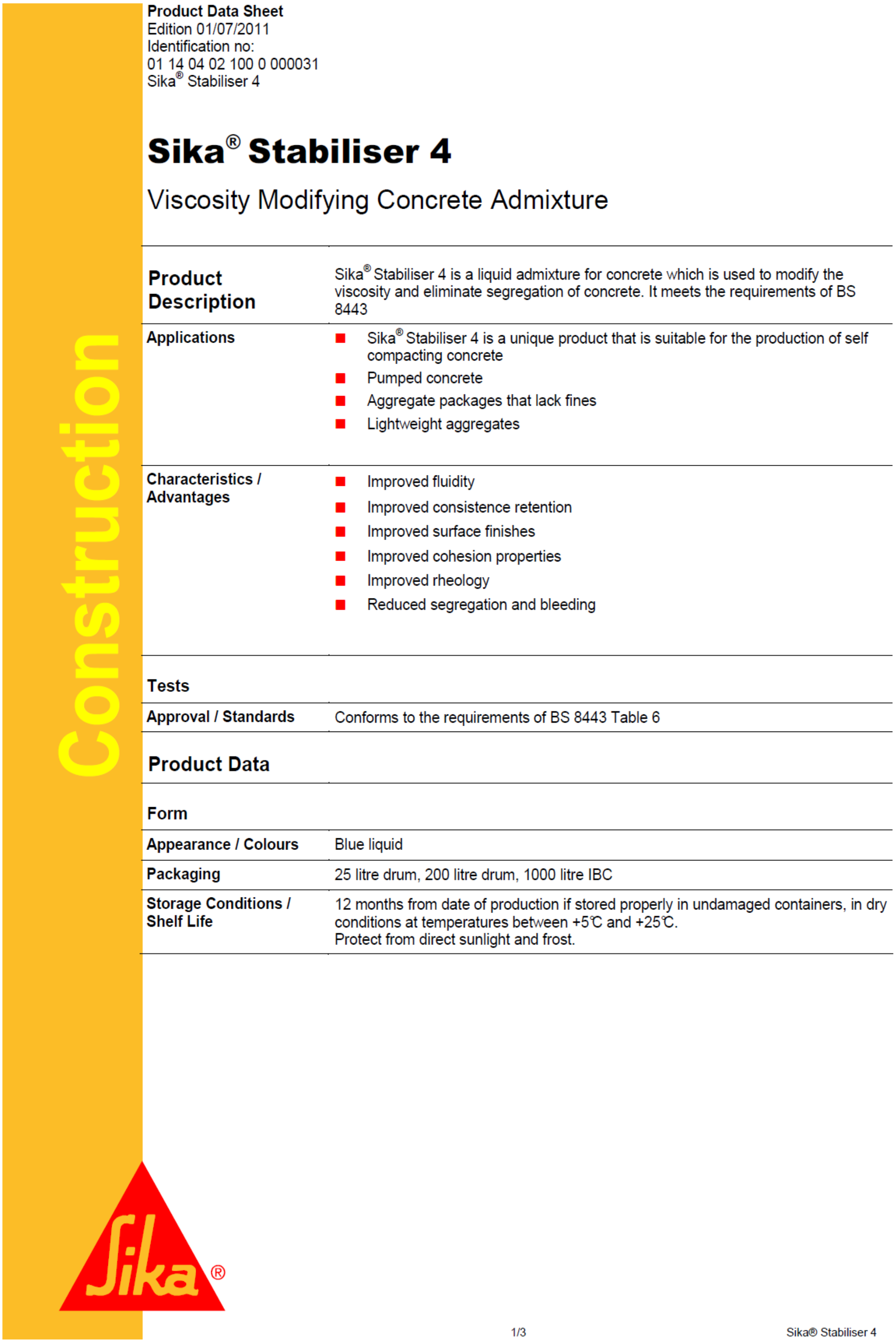
Sika Limited
Watchmead
Welwyn Garden City
Hertfordshire
AL7 1BQ
United Kingdom

Phone +44 1707 394444
Telefax +44 1707 329129
www.sika.co.uk
email: sales@uk.sika.com

Certificate No. EMS 4308

Certificate No. FM 12504

A4. 2 Sika Stabiliser 4



Product Data Sheet
Edition 01/07/2011
Identification no:
01 14 04 02 100 0 000031
Sika® Stabiliser 4

Sika® Stabiliser 4

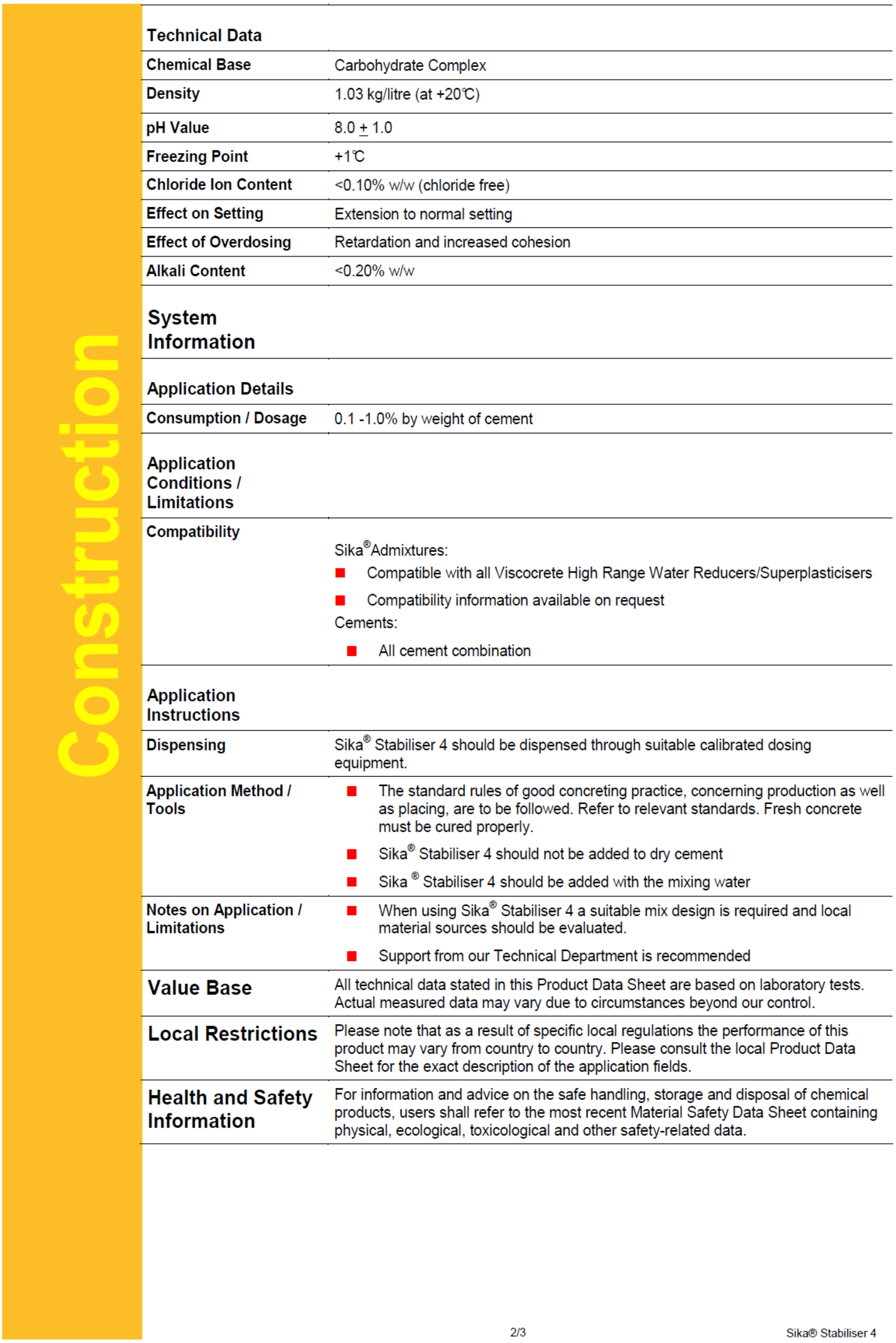
Viscosity Modifying Concrete Admixture

Product Description	Sika® Stabiliser 4 is a liquid admixture for concrete which is used to modify the viscosity and eliminate segregation of concrete. It meets the requirements of BS 8443
Applications	■ Sika® Stabiliser 4 is a unique product that is suitable for the production of self compacting concrete ■ Pumped concrete ■ Aggregate packages that lack fines ■ Lightweight aggregates
Characteristics / Advantages	■ Improved fluidity ■ Improved consistence retention ■ Improved surface finishes ■ Improved cohesion properties ■ Improved rheology ■ Reduced segregation and bleeding
Tests	
Approval / Standards	Conforms to the requirements of BS 8443 Table 6

Product Data

Form	
Appearance / Colours	Blue liquid
Packaging	25 litre drum, 200 litre drum, 1000 litre IBC
Storage Conditions / Shelf Life	12 months from date of production if stored properly in undamaged containers, in dry conditions at temperatures between +5℃ and +25℃. Protect from direct sunlight and frost.

1/3 Sika® Stabiliser 4



Technical Data

Chemical Base	Carbohydrate Complex
Density	1.03 kg/litre (at +20°C)
pH Value	8.0 ± 1.0
Freezing Point	+1°C
Chloride Ion Content	<0.10% w/w (chloride free)
Effect on Setting	Extension to normal setting
Effect of Overdosing	Retardation and increased cohesion
Alkali Content	<0.20% w/w

System Information

Application Details

Consumption / Dosage	0.1 -1.0% by weight of cement

Application Conditions / Limitations

Compatibility	Sika® Admixtures: ■ Compatible with all Viscocrete High Range Water Reducers/Superplasticisers ■ Compatibility information available on request Cements: ■ All cement combination

Application Instructions

Dispensing	Sika® Stabiliser 4 should be dispensed through suitable calibrated dosing equipment.
Application Method / Tools	■ The standard rules of good concreting practice, concerning production as well as placing, are to be followed. Refer to relevant standards. Fresh concrete must be cured properly. ■ Sika® Stabiliser 4 should not be added to dry cement ■ Sika ® Stabiliser 4 should be added with the mixing water
Notes on Application / Limitations	■ When using Sika® Stabiliser 4 a suitable mix design is required and local material sources should be evaluated. ■ Support from our Technical Department is recommended

Value Base	All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.
Local Restrictions	Please note that as a result of specific local regulations the performance of this product may vary from country to country. Please consult the local Product Data Sheet for the exact description of the application fields.
Health and Safety Information	For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.

Legal Notes

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

Sika Limited
Watchmead
Welwyn Garden City
Hertfordshire
AL7 1BQ
United Kingdom

Phone +44 1707 394444
Telefax +44 1707 329129
www.sika.co.uk
email: sales@uk.sika.com

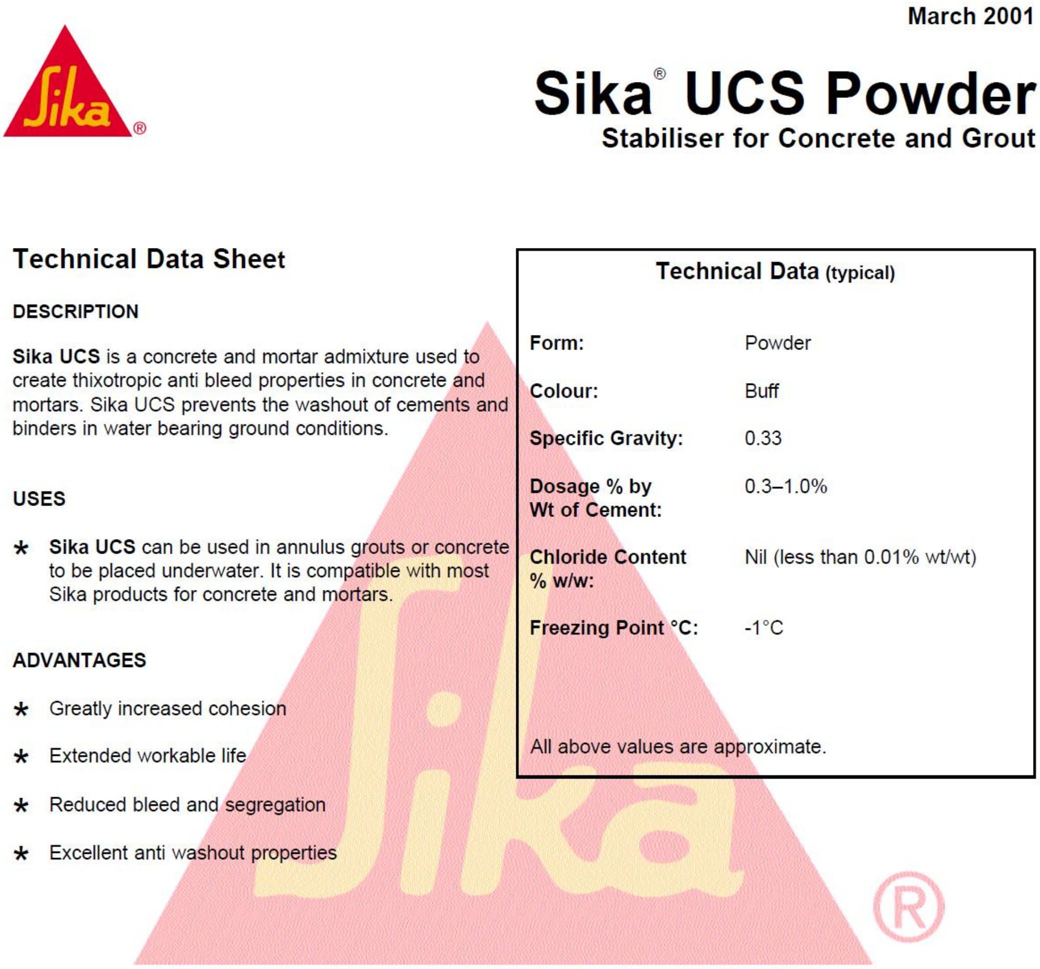
Certificate No. EMS 4308

Certificate No. FM 12504

3/3

Sika® Stabiliser 4

A4. 3 Sika UCS Powder



March 2001

Sika® UCS Powder

Stabiliser for Concrete and Grout

Technical Data Sheet

DESCRIPTION

Sika UCS is a concrete and mortar admixture used to create thixotropic anti bleed properties in concrete and mortars. Sika UCS prevents the washout of cements and binders in water bearing ground conditions.

USES

- **Sika UCS** can be used in annulus grouts or concrete to be placed underwater. It is compatible with most Sika products for concrete and mortars.

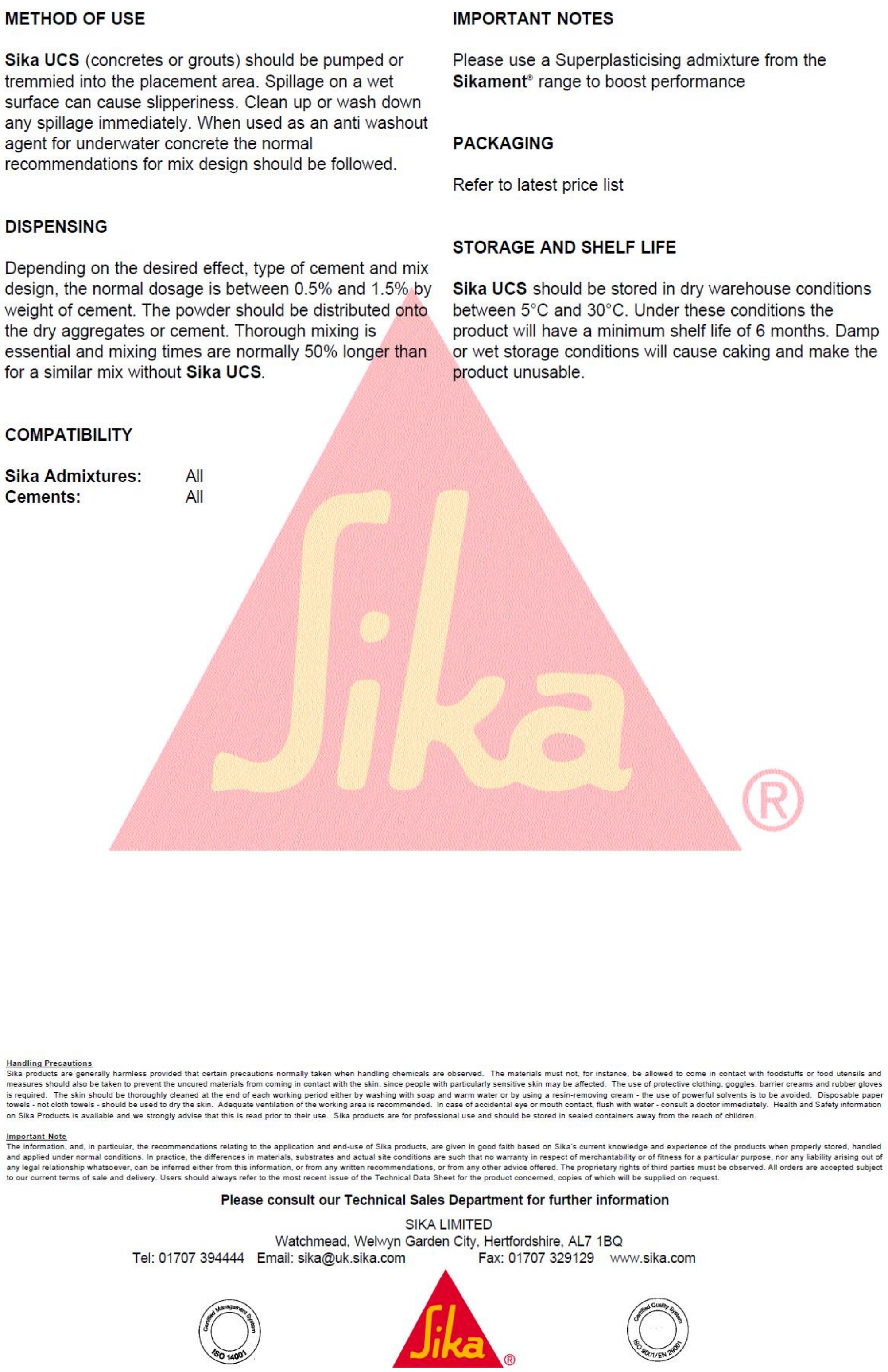
ADVANTAGES

- Greatly increased cohesion
- Extended workable life
- Reduced bleed and segregation
- Excellent anti washout properties

Technical Data (typical)

Form:	Powder
Colour:	Buff
Specific Gravity:	0.33
Dosage % by Wt of Cement:	0.3–1.0%
Chloride Content % w/w:	Nil (less than 0.01% wt/wt)
Freezing Point °C:	-1°C

All above values are approximate.



METHOD OF USE

Sika UCS (concretes or grouts) should be pumped or tremmied into the placement area. Spillage on a wet surface can cause slipperiness. Clean up or wash down any spillage immediately. When used as an anti washout agent for underwater concrete the normal recommendations for mix design should be followed.

DISPENSING

Depending on the desired effect, type of cement and mix design, the normal dosage is between 0.5% and 1.5% by weight of cement. The powder should be distributed onto the dry aggregates or cement. Thorough mixing is essential and mixing times are normally 50% longer than for a similar mix without **Sika UCS**.

COMPATIBILITY

Sika Admixtures:	All
Cements:	All

IMPORTANT NOTES

Please use a Superplasticising admixture from the **Sikament**® range to boost performance

PACKAGING

Refer to latest price list

STORAGE AND SHELF LIFE

Sika UCS should be stored in dry warehouse conditions between 5°C and 30°C. Under these conditions the product will have a minimum shelf life of 6 months. Damp or wet storage conditions will cause caking and make the product unusable.

Handling Precautions
Sika products are generally harmless provided that certain precautions normally taken when handling chemicals are observed. The materials must not, for instance, be allowed to come in contact with foodstuffs or food utensils and measures should also be taken to prevent the uncured materials from coming in contact with the skin, since people with particularly sensitive skin may be affected. The use of protective clothing, goggles, barrier creams and rubber gloves is required. The skin should be thoroughly cleaned at the end of each working period either by washing with soap and warm water or by using a resin-removing cream - the use of powerful solvents is to be avoided. Disposable paper towels - not cloth towels - should be used to dry the skin. Adequate ventilation of the working area is recommended. In case of accidental eye or mouth contact, flush with water - consult a doctor immediately. Health and Safety information on Sika Products is available and we strongly advise that this is read prior to their use. Sika products are for professional use and should be stored in sealed containers away from the reach of children.

Important Note
The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users should always refer to the most recent issue of the Technical Data Sheet for the product concerned, copies of which will be supplied on request.

Please consult our Technical Sales Department for further information

SIKA LIMITED
Watchmead, Welwyn Garden City, Hertfordshire, AL7 1BQ
Tel: 01707 394444 Email: sika@uk.sika.com Fax: 01707 329129 www.sika.com

Appendix 5 Mix Proportions

Table A5-1 Self-compacting concrete mix proportions

		Proportions											
Mix No.	**Mix Ref.**	**PC**	**LSP**		**GGBS**	**Fly Ash**	**Fine Aggregate**	**Coarse Aggregate**		**Water**	**w/p**	**SP**	**VMA**
			B10	**B45**			**0/4**	**4/10**	**10/20**				
		kg/m^3									**by wt***	**% by wt powder**	**% by vol**
1	SCC-C	520	0	0	0	0	784	301	602	174	0.32	1.5	0.0
2	SCC-L10	468	33	11	0	0	784	301	602	174	0.33	1.3	0.1
3	SCC-L20	416	67	22	0	0	784	301	602	174	0.33	1.0	0.1
4	SCC-L30	364	100	33	0	0	784	301	602	174	0.33	0.9	0.1
5	SCC-G20	416	0	0	96	0	784	301	602	174	0.33	1.3	0.1
6	SCC-G40	312	0	0	191	0	784	301	602	174	0.33	1.1	0.1
7	SCC-G60	208	0	0	287	0	784	301	602	174	0.34	0.9	0.1
8	SCC-G80	104	0	0	383	0	784	301	602	174	0.34	1.0	0.2
9	SCC-F20	416	0	0	0	74	784	301	602	174	0.34	1.1	0.1
10	SCC-F40	312	0	0	0	147	784	301	602	174	0.36	1.0	0.0

11	SCC-F60	208	0	0	0	221	784	301	602	174	0.39	0.9	0.1
12	SCC-F80	104	0	0	0	294	784	301	602	174	0.41	0.8	0.2
13	SCC-TB-G20	333	53	18	96	0	784	301	602	174	0.33	1.1	0.2
14	SCC-TB-G40	250	40	13	191	0	784	301	602	174	0.34	1.0	0.2
15	SCC-TB-G60	166	27	9	287	0	784	301	602	174	0.34	1.0	0.2
16	SCC-TB-G80	83	13	4	383	0	784	301	602	174	0.34	0.9	0.2
17	SCC-TB-F20	333	53	18	0	74	784	301	602	174	0.35	1.0	0.2
18	SCC-TB-F40	250	40	13	0	147	784	301	602	174	0.37	0.8	0.25
19	SCC-TB-F60	166	27	9	0	221	784	301	602	174	0.39	0.8	0.3
20	SCC-TB-F80	83	13	4	0	294	784	301	602	174	0.42	0.7	0.3

*** 1.002 by vol. for all mixes**

Table A5-2 Flowing concrete mix proportions

		Proportions										
Mix No.	**Mix Ref.**	**PC**	**LSP**		**GGBS**	**Fly Ash**	**Fine Aggregate**	**Coarse Aggregate**		**Water**	**w/p**	**SP**
			B10	**B45**			**0/4**	**4/10**	**10/20**			
		kg/m^3									**by wt***	**% by wt powder**
21	FC-C	443	0	0	0	0	661	367	734	195	0.44	0.5
22	FC-L20	354	57	19	0	0	661	367	734	195	0.45	0.3
23	FC-G40	266	0	0	163	0	661	367	734	195	0.45	0.2
24	FC-F20	354	0	0	0	63	661	367	734	195	0.47	0.1
25	FC-TB-G40	213	34	11	163	0	661	367	734	195	0.46	0.3
26	FC-TB-F20	284	46	15	0	63	661	367	734	195	0.48	0.1

*** 1.387 by vol. for all mixes**

Table A5-3 Underwater concrete mix proportions

		Proportions											
Mix No.	**Mix Ref.**	**PC**	**LSP**		**GGBS**	**Fly Ash**	**Fine Aggregate**	**Coarse Aggregate**		**Water**	**w/p**	**SP**	**AWA**
			B10	**B45**			**0/4**	**4/10**	**10/20**				
		kg/m^3									**by wt***	**% by wt powder**	**% by vol**
27	UWC-C	475	0	0	0	0	848	275	551	209	0.44	0.7	0.5
28	UWC-L20	380	61	20	0	0	848	275	551	209	0.45	0.5	0.5
29	UWC-G40	285	0	0	175	0	848	275	551	209	0.45	0.4	0.6
30	UWC-F20	380	0	0	0	67	848	275	551	209	0.47	0.5	0.7
31	UWC-TB-G40	228	37	12	175	0	848	275	551	209	0.46	0.4	0.6
32	UWC-TB-F20	304	49	16	0	67	848	275	551	209	0.48	0.5	0.6

*** 1.386 by vol. for all mixes**

Appendix 6 Tabulated Results – Hardened Concrete Properties

A6. 1 Self-compacting concrete

Table A6-1 Tabulated results for self-compacting concrete

Test Specimen		**Cubes**								**Cylinders**							**Prisms**					
Mix No	Age	Weight (Air)	Weight (Water)	Density	UPV	UPV	Avg. UPV	Compressive Strength	Avg. Compressive Strength	Weight (Air)	Weight (Water)	Density	Load	Splitting Strength	Avg. Splitting Strength	RCPT Charge Passed (Coloumbs)	Weight (Air)	Weight (Water)	Density	Natural frequency	E_d	Avg. E_d
	(days)	(kg)	(kg)	(kg/m^3)	Time	(km/s)	(km/s)	(MPa)	(Mpa)	(kg)	(kg)	(kg/m^3)	(kN)	(MPa)	(Mpa)		(kg)	(kg)	(kg/m^3)	(Hz)	(Gpa)	(Gpa)
1	1	2.3555	1.339	2317	22.9	4.37	4.42	34.6	33.33								12.506	7.256	2382	4197	43.1	43.0
Control		2.399	1.39	2378	22.75	4.40		32.5									11.843	6.861	2377	4188	42.9	
Mix		2.3495	1.353	2358	22.25	4.49		32.9														
	3	2.3795	1.38	2381	21.1	4.74	4.70	46.32	49.61								12.5205	7.288	2393	4275	45.0	44.9
		2.3725	1.373	2374	21.2	4.72		52.74									11.8535	6.875	2381	4275	44.7	
		2.2995	1.326	2362	21.5	4.65		49.77														
	7	2.351	1.358	2368	21.2	4.72	4.73	62	55.87							5650	12.5265	7.284	2389	4355	46.6	46.7
		2.397	1.395	2392	21.1	4.74		52.75									11.861	6.91	2396	4355	46.7	
		2.386	1.386	2386	21.1	4.74		52.85														
	28	2.264	1.303	2356	20.8	4.81	4.85	54.5	59.70	3.72	2.17	2394	179	5.68	5.68	2774	12.5465	7.296	2390	4447	48.6	48.6
		2.397	1.405	2416	20.3	4.93		69.7		3.73	2.16	2379	182	5.78			11.882	6.905	2387	4447	48.5	
		2.382	1.387	2394	20.8	4.81		54.9		3.69	2.13	2371	175	5.57								
	56	2.3595	1.367	2377	20.7	4.83	4.87	66.6	66.38								12.561	7.306	2390	4480	49.3	49.3
		2.383	1.372	2357	20.8	4.81		66.4									11.8985	6.911	2386	4480	49.2	
		2.394	1.393	2392	20.1	4.98		66.15														

Appendix 6 Tabulated Results – Hardened Concrete Properties

	91	2.3885	1.3795	2367	20.1	4.98	4.95	75.8	70.07	3.7535	2.185	2393	197	6.27	6.50	1704	12.5675	7.311	2391	4497	49.7	49.7
		2.401	1.405	2411	20.1	4.98		71		3.733	2.164	2379	210	6.68			11.9015	6.917	2388	4500	49.7	
		2.376	1.371	2364	20.4	4.90		63.4		3.752	2.182	2390	206	6.56								
2	1	2.4205	1.409	2393	21.6	4.63	4.61	27.65	26.32								11.553	6.644	2353	3950	36.7	37.1
10% LP		2.4015	1.396	2388	21.7	4.61		26.15									11.691	6.753	2368	3978	37.5	
		2.3295	1.351	2381	21.8	4.59		25.15														
	3	2.3685	1.3585	2345	21.3	4.69	4.71	46.25	43.45								11.635	6.714	2364	4234	42.4	42.8
		2.3425	1.3515	2364	21.2	4.72		41.15									11.7625	6.813	2377	4266	43.2	
		2.3785	1.3745	2369	21.2	4.72		42.95														
	7	2.388	1.385	2381	21	4.76	4.75	51.4	50.28							8806	11.6475	6.728	2368	4330	44.4	44.9
		2.3215	1.33	2341	21.1	4.74		49.35									11.781	6.838	2383	4365	45.4	
		2.421	1.408	2390	21	4.76		50.1														
	28	2.374	1.383	2396	20.7	4.83	4.82	59.45	57.08	3.679	2.091	2317	157	5.00	5.02	3636	11.6645	6.752	2374	4440	46.8	47.3
		2.3255	1.317	2306	20.8	4.81		56.2		3.729	2.134	2338	164	5.22			11.788	6.859	2392	4470	47.8	
		2.3825	1.317	2236	20.8	4.81		55.6		3.703	2.131	2356	152	4.84								
	56	2.3205	1.341	2369	20.6	4.85	4.85	59	59.07								11.6615	6.747	2373	4479	47.6	47.9
		2.382	1.378	2373	20.6	4.85		57.4									11.7895	6.8435	2384	4497	48.2	
		2.3935	1.387	2378	20.6	4.85		60.8														
	91	2.4345	1.4115	2380	20.4	4.90	4.91	77.84	74.24	3.7275	2.1555	2371	167.1	5.32	5.71	2603	11.684	6.757	2371	4487	47.7	48.2
		2.419	1.414	2407	20.4	4.90		73.38		3.7455	2.1555	2356	184.9	5.89			11.806	6.851	2383	4522	48.7	
		2.395	1.391	2385	20.3	4.93		71.49		3.717	2.148	2369	186	5.92								
3	1	2.3135	1.319	2326	22.9	4.37	4.43	25.75	25.40								11.6305	6.6735	2346	3870	35.1	34.8
20% LP		2.357	1.356	2355	22.5	4.44		25.9									11.615	6.649	2339	3840	34.5	
		2.3315	1.3365	2343	22.3	4.48		24.55														
	3	2.336	1.344	2355	21.6	4.63	4.65	36.15	36.12								11.71	6.73	2351	4118	39.9	39.8

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2.364	1.365	2366	21.4	4.67		34.4									11.723	6.729	2347	4117	39.8	
		2.354	1.3505	2346	21.5	4.65		37.8														
	7	2.336	1.335	2334	21.1	4.74	4.75	37.65	40.75							12180	11.721	6.744	2355	4247	42.5	42.3
		2.379	1.364	2344	21	4.76		45.55									11.734	6.747	2353	4227	42.0	
		2.359	1.354	2347	21.1	4.74		39.05														
	28	2.378	1.371	2361	20.8	4.81	4.81	42.8	46.97	3.6265	2.067	2325	91	2.90	3.11	10090	11.74	6.765	2360	4352	44.7	44.5
		2.386	1.381	2374	20.8	4.81		51.9		3.703	2.122	2342	94	2.99			11.746	6.763	2357	4337	44.3	
		2.359	1.358	2357	20.8	4.81		46.2		3.665	2.104	2348	108	3.44								
	56	2.3595	1.3595	2360	20.5	4.88	4.87	49.7	53.25								11.74	6.767	2361	4386	45.4	45.4
		2.422	1.405	2382	20.5	4.88		55.75									11.747	6.767	2359	4385	45.4	
		2.317	1.336	2362	20.6	4.85		54.3														
	91	2.369	1.364	2357	20.3	4.93	4.92	66.34	66.18	3.742	2.174	2386	142.6	4.54	4.65	4929	11.748	6.777	2363	4410	46.0	45.9
		2.374	1.364	2350	20.4	4.90		65.8		3.664	2.099	2341	155.6	4.95			11.758	6.774	2359	4410	45.9	
		2.378	1.37	2359	20.3	4.93		66.4		3.716	2.146	2367	139.6	4.44								
4	1	2.329	1.328	2327	23.4	4.27	4.31	21.4	20.53								11.772	6.778	2357	3845	34.8	33.9
30% LP		2.305	1.327	2357	23.1	4.33		18.75									11.447	6.537	2331	3760	33.0	
		2.338	1.3445	2353	23.1	4.33		21.45														
	3	2.3645	1.37	2378	21.1	4.74	4.70	32.1	29.75								11.856	6.845	2366	4160	40.9	40.0
		2.368	1.3695	2372	21.4	4.67		30.05									11.525	6.613	2346	4084	39.1	
		2.353	1.35	2346	21.4	4.67		27.1														
	7	2.3985	1.3815	2358	21.3	4.69	4.74	41.4	41.17							5486	11.8735	6.856	2366	4277	43.3	42.4
		2.3475	1.353	2360	21.1	4.74		39.25									11.5395	6.625	2348	4200	41.4	
		2.4145	1.401	2382	20.9	4.78		42.85														
	28	2.404	1.398	2390	20.7	4.83	4.84	48.3	49.48	3.718	2.148	2368	130.5	4.15	4.22	4712	11.886	6.865	2367	4381	45.4	44.7
		2.3795	1.371	2359	20.7	4.83		51.25		3.715	2.145	2366	129	4.11			11.545	6.633	2350	4325	44.0	

		2.416	1.4	2378	20.6	4.85		48.9		3.725	2.153	2370	138	4.39								
	56	2.3635	1.357	2348	20.4	4.90	4.89	59.1	57.45								11.885	6.875	2372	4426	46.5	45.6
		2.361	1.37	2382	20.5	4.88		56.5									11.555	6.643	2352	4359	44.7	
		2.3475	1.337	2323	20.4	4.90		56.75														
	91	2.398	1.387	2372	20.3	4.93	4.93	66.3	64.36	3.725	2.156	2374	166.3	5.29	4.70	2513	11.895	6.878	2371	4450	47.0	46.1
		2.384	1.377	2367	20.3	4.93		67.42		3.7055	2.137	2362	140.7	4.48			11.565	6.652	2354	4380	45.2	
		2.3525	1.362	2375	20.3	4.93		59.37		3.7335	2.162	2376	135.6	4.32								
5	1	2.3905	1.384	2375	22.65	4.42	4.42	24.12	25.16								12.479	7.196	2362	3857	36.1	37.4
20% GGBS		2.3525	1.361	2373	22.6	4.42		26.85									12.529	7.287	2390	3970	38.7	
		2.3755	1.373	2370	22.7	4.41		24.51														
	3	2.408	1.403	2396	21.5	4.65	4.67	44.37	43.51								12.5575	7.274	2377	4131	41.7	42.6
		2.401	1.399	2396	21.3	4.69		41.76									12.5945	7.332	2393	4203	43.5	
		2.375	1.3745	2374	21.4	4.67		44.4														
	7	2.41	1.401	2389	20.8	4.81	4.82	55	54.43							5044	12.5755	7.285	2377	4255	44.2	45.1
		2.402	1.388	2369	20.7	4.83		55.55									12.611	7.346	2395	4323	46.0	
		2.383	1.383	2383	20.7	4.83		52.75														
	28	2.369	1.3705	2373	21	4.76	4.77	62.75	59.40	3.719	2.148	2367	157	5.00	5.02	2857	12.5925	7.302	2380	4407	47.5	48.5
		2.3995	1.389	2375	20.9	4.78		61.2		3.6815	2.1115	2345	172	5.47			12.632	7.3605	2396	4477	49.4	
		2.388	1.392	2398	21	4.76		54.25		3.7545	2.184	2391	144	4.58								
	56	2.4	1.396	2390	20.6	4.85	4.87	67.25	70.93								12.6075	7.31	2380	4453	48.5	49.5
		2.4155	1.401	2381	20.6	4.85		70.3									12.639	7.369	2398	4523	50.4	
		2.42	1.411	2398	20.4	4.90		75.25														
	91	2.3915	1.3845	2375	20.1	4.98	4.99	73.6	73.60	3.7365	2.163	2375	163.5	5.20	5.25	2026	12.639	7.317	2375	4476	48.9	50.0
		2.4045	1.4015	2397	20	5		73.55		3.7125	2.151	2378	163	5.19			12.6075	7.374	2409	4543	51.1	
		2.4245	1.405	2378	20	5		73.65		3.7125	2.154	2382	168	5.35								

Appendix 6 Tabulated Results – Hardened Concrete Properties

6	1	2.358	1.353	2346	24.3	4.12	4.18	15.7	16.52								12.284	7.073	2357	3708	33.3	32.9
40% GGBS		2.391	1.379	2363	23.7	4.22		16.95									12.4315	7.1425	2350	3668	32.5	
		2.388	1.377	2362	23.8	4.20		16.9														
	3	2.3585	1.367	2379	21.4	4.67	4.65	25.95	32.25								12.363	7.146	2370	4044	39.8	39.5
		2.38	1.375	2368	21.6	4.63		36.05									12.517	7.219	2363	4013	39.1	
		2.366	1.367	2368	21.5	4.65		34.75														
	7	2.373	1.3785	2386	21.3	4.69	4.68	39.5	42.18							4114	12.3775	7.162	2373	4164	42.3	42.0
		2.3705	1.3755	2382	21.4	4.67		41.15									12.532	7.237	2367	4141	41.7	
		2.391	1.3815	2368	21.4	4.67		45.9														
	28	2.401	1.396	2389	20.6	4.85	4.85	66.6	62.57	3.6685	2.1085	2352	200	6.37	5.87	1454	12.397	7.182	2377	4409	47.5	47.2
		2.398	1.396	2393	20.6	4.85		59.1		3.7045	2.1465	2378	187	5.95			12.5595	7.257	2369	4390	46.9	
		2.366	1.3755	2389	20.6	4.85		62		3.6905	2.1305	2366	166.5	5.30								
	56	2.353	1.364	2379	20.4	4.90	4.89	63.5	64.92								12.41	7.189	2377	4463	48.7	48.4
		2.426	1.408	2383	20.4	4.90		66.25									12.5655	7.264	2370	4447	48.2	
		2.431	1.413	2388	20.5	4.88		65														
	91	2.3735	1.375	2377	20.2	4.95	4.95	70.25	69.78	3.7025	2.144	2376	185	5.89	6.27	611	12.414	7.192	2377	4479	49.0	48.9
		2.4315	1.408	2376	20.2	4.95		67.3		3.6655	2.1215	2374	205	6.53			12.573	7.264	2368	4477	48.8	
		2.389	1.389	2389	20.2	4.95		71.8		3.6725	2.1055	2344	201	6.40								
7	1	2.3375	1.335	2332	24.6	4.07	4.10	10.9	11.07								12.2425	6.955	2315	3423	27.9	28.6
60% GGBS		2.3205	1.3315	2346	24.1	4.15		11.15									12.2265	7.017	2347	3490	29.4	
		2.3215	1.325	2330	24.4	4.10		11.15														
	3	2.408	1.3995	2388	22.1	4.52	4.51	24.05	25.00								12.3415	7.048	2331	3863	35.8	36.5
		2.361	1.366	2373	22.2	4.50		25.45									12.312	7.097	2361	3920	37.3	
		2.3665	1.366	2365	22.2	4.50		25.5														
	7	2.37	1.3705	2371	21.8	4.59	4.57	36.2	35.42							3135	12.36	7.0675	2335	3936	37.2	37.8
		2.3735	1.3715	2369	21.6	4.63		33.85									12.336	7.115	2363	3975	38.4	

		2.371	1.361	2348	22.2	4.50		36.2														
	28	2.3265	1.3415	2362	21.3	4.69	4.69	44	46.07	3.689	2.119	2350	153.5	4.89	4.84	1594	12.377	7.081	2337	4245	43.3	43.8
		2.3905	1.375	2354	21.3	4.69		45.75		3.7005	2.1275	2353	163	5.19			12.3475	7.1235	2364	4274	44.4	
		2.3745	1.3675	2358	21.4	4.67		48.45		3.707	2.141	2367	139.5	4.44								
	56	2.351	1.3505	2350	21	4.76	4.77	54.45	56.35								12.379	7.088	2340	4342	45.4	46.0
		2.348	1.3505	2354	20.9	4.78		54.5									12.3545	7.135	2367	4377	46.6	
		2.3485	1.355	2364	21	4.76		60.1														
	91	2.36	1.317	2263	20.5	4.88	4.88	58.95	60.87	3.679	2.131	2377	173	5.51	5.60	699.5	12.349	7.095	2350	4384	46.4	46.9
		2.3805	1.328	2262	20.5	4.88		61.9		3.695	2.146	2385	180	5.73			12.388	7.113	2348	4430	47.4	
		2.3505	1.311	2261	20.5	4.88		61.75		3.694	2.142	2380	175	5.57								
8	1	2.343	1.342	2341	26.7	3.75	3.74	5.55	5.65								12.348	7.0555	2333	3003	21.6	22.0
80% GGBS		2.325	1.321	2316	27.3	3.66		5.45									12.198	6.973	2335	3055	22.4	
		2.382	1.365	2342	26.3	3.80		5.95														
	3	2.333	1.338	2345	23.1	4.33	4.39	21.25	21.82								12.431	7.126	2343	3679	32.6	33.1
		2.355	1.352	2348	22.9	4.37		22.1									12.2815	7.045	2345	3727	33.5	
		2.385	1.372	2354	22.3	4.48		22.1														
	7	2.357	1.356	2355	22.3	4.48	4.46	31	30.00							1240	12.44	7.132	2344	3780	34.4	34.9
		2.359	1.354	2347	22.4	4.46		28.4									12.2895	7.05	2346	3828	35.3	
		2.3315	1.333	2335	22.5	4.44		30.6														
	28	2.4175	1.392	2357	21.3	4.69	4.68	42	44.02	3.6605	2.099	2344	128	4.07	3.45	621.3	12.4505	7.14	2345	4137	41.3	41.8
		2.366	1.359	2350	21.4	4.67		45.05		3.6575	2.101	2350	95	3.02			12.299	7.0575	2346	4192	42.4	
		2.374	1.37	2365	21.4	4.67		45		3.669	2.105	2346	102.5	3.26								
	56	2.334	1.331	2327	21.3	4.69	4.70	50.35	46.42								12.4535	7.1435	2345	4217	42.9	43.4
		2.3505	1.343	2333	21.3	4.69		44.75									12.302	7.06	2347	4264	43.9	
		2.328	1.335	2344	21.2	4.72		44.15														
	91	2.337	1.333	2328	21.1	4.74	4.75	49.4	48.10	3.654	2.085	2329	128	4.07	4.12	626.3	12.458	7.158	2351	4240	43.4	43.8

		2.3405	1.335	2328	21.1	4.74		47.75		3.664	2.092	2331	125.5	3.99			12.304	7.046	2340	4283	44.1	
		2.3645	1.347	2324	21	4.76		47.15		3.6675	2.108	2352	135	4.30								
9	1	2.313	1.313	2313	22.8	4.39	4.53	31.2	28.17								12.4335	7.125	2342	3946	37.5	37.8
20% FA		2.3625	1.3555	2346	21.4	4.67		24.9									12.2415	7.042	2354	3964	38.0	
		2.295	1.3105	2331	22	4.55		28.4														
	3	2.3555	1.363	2373	21.4	4.67	4.71	46.1	43.50								12.513	7.185	2349	4175	42.1	42.2
		2.3575	1.351	2342	21.5	4.65		39.45									12.308	7.084	2356	4175	42.2	
		2.4135	1.404	2391	20.8	4.81		44.95														
	7	2.3405	1.3485	2359	21	4.76	4.78	44.3	45.87							5762	12.5295	7.204	2353	4258	43.9	43.9
		2.3675	1.3665	2365	20.8	4.81		44.85									12.3205	7.099	2360	4260	44.0	
		2.3555	1.3605	2367	21	4.76		48.45														
	28	2.3285	1.343	2363	20.7	4.83	4.83	59.05	56.52	3.6575	2.108	2360	129.5	4.12	4.09	2403	12.5515	7.2235	2356	4392	46.7	46.7
		2.3925	1.393	2394	20.6	4.85		49.15		3.662	2.107	2355	151.5	4.82			12.342	7.1175	2362	4385	46.7	
		2.3915	1.384	2374	20.8	4.81		61.35		3.684	2.125	2363	104.5	3.33								
	56	2.35	1.36	2374	20.4	4.90	4.92	67.25	67.90								12.552	7.23	2359	4457	48.2	48.2
		2.355	1.365	2379	20.3	4.93		66.5									12.341	7.123	2365	4457	48.3	
		2.3745	1.373	2371	20.3	4.93		69.95														
	91	2.3565	1.361	2367	20.2	4.95	4.94	69.55	71.00	3.7315	2.152	2362	141.5	4.50	4.98	585.4	12.566	7.235	2357	4497	49.0	49.1
		2.3705	1.367	2362	20.3	4.93		71.25		3.727	2.157	2374	158.5	5.05			12.3505	7.128	2365	4500	49.2	
		2.3815	1.376	2368	20.2	4.95		72.2		3.704	2.14	2368	169	5.38								
10	1	2.3075	1.309	2311	22.9	4.37	4.35	17.9	16.93								12.166	6.9125	2316	3655	31.8	31.5
40% FA		2.284	1.291	2300	23	4.35		16.35									12.323	6.974	2304	3625	31.1	
		2.325	1.331	2339	23	4.35		16.55														
	3	2.331	1.325	2317	22.4	4.46	4.46	31.4	29.85								12.258	6.987	2326	3972	37.7	37.4
		2.31	1.312	2315	22.4	4.46		29									12.4355	7.068	2317	3950	37.2	

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2.3175	1.3335	2355	22.4	4.46		29.15														
	7	2.338	1.338	2338	21.8	4.59	4.59	37.1	37.45							9206	12.275	7.005	2329	4065	39.6	39.4
		2.358	1.3415	2320	21.9	4.57		39.95									12.445	7.088	2323	4048	39.1	
		2.354	1.346	2335	21.6	4.63		35.3														
	28	2.357	1.35	2341	21	4.76	4.78	49.7	50.17	3.6535	2.089	2335	136.5	4.34	4.28	2701	12.2975	7.031	2335	4274	43.9	43.6
		2.375	1.369	2361	20.8	4.81		51.05		3.6525	2.085	2330	115	3.66			12.467	7.116	2330	4249	43.2	
		2.3405	1.35	2363	20.9	4.78		49.75		3.6585	2.09	2332	151.5	4.82								
	56	2.3325	1.3355	2340	20.6	4.85	4.86	57.9	58.68								12.3025	6.982	2312	4350	45.0	45.1
		2.3635	1.339	2307	20.5	4.88		58.55									12.4755	7.1425	2339	4337	45.2	
		2.3055	1.3255	2353	20.6	4.85		59.6														
	91	2.3855	1.3715	2353	20.4	4.90	4.90	63.4	61.27	3.656	2.085	2327	122.5	3.90	4.64	793.2	12.299	7.032	2335	4379	46.0	46.1
		2.362	1.352	2339	20.4	4.90		60.8		3.597	2.036	2304	161.5	5.14			12.476	7.143	2339	4377	46.1	
		2.3195	1.3275	2338	20.4	4.90		59.6		3.5625	2.028	2322	153.5	4.89								
11	1	2.297	1.291	2283	25.5	3.92	3.85	4.35	4.13								11.856	6.6915	2296	2967	20.8	21.1
60% FA		2.265	1.2605	2255	27	3.70		4.15									12.028	6.797	2299	3005	21.3	
		2.33	1.322	2312	25.4	3.94		3.9														
	3	2.28	1.272	2262	23.6	4.24	4.27	12.2	12.15								11.927	6.742	2300	3662	31.7	32.0
		2.284	1.2705	2254	23.6	4.24		11.75									12.095	6.845	2304	3686	32.2	
		2.301	1.2885	2273	23.1	4.33		12.5														
	7	2.22	1.229	2240	23.7	4.22	4.28	16.4	16.55							8333	11.941	6.7585	2304	3757	33.4	33.7
		2.308	1.2975	2284	22.7	4.41		16.6									12.104	6.858	2307	3784	34.0	
		2.2885	1.2665	2239	23.7	4.22		16.65														
	28	2.2765	1.2715	2265	22.5	4.44	4.50	28.95	27.95	3.5365	1.96	2243	99.5	3.17	2.82	2283	11.941	6.75	2300	3940	36.7	37.0
		2.3115	1.313	2315	22.5	4.44		27.9		3.533	1.972	2263	80	2.55			12.117	6.862	2306	3968	37.3	
		2.3555	1.342	2324	21.7	4.61		27		3.528	1.957	2246	86.5	2.75								
	56	2.294	1.281	2265	22.3	4.48	4.55	36	32.80								11.9405	6.7615	2306	4068	39.2	39.5

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2.291	1.297	2305	21.8	4.59		31.4									12.12	6.87	2309	4092	39.7	
		2.292	1.295	2299	21.8	4.59		31														
	91	2.3555	1.3525	2348	20.8	4.81	4.77	36.5	37.18	3.53	2.003	2312	94.5	3.01	2.96	1056	11.954	6.771	2306	4145	40.7	40.9
		2.357	1.341	2320	21	4.76		36.35		3.5385	1.9805	2271	90	2.86			12.128	6.879	2311	4155	41.0	
		2.2855	1.301	2321	21.1	4.74		38.7		3.469	1.929	2253	94.5	3.01								
12	1	2.2295	1.23	2231	31.4	3.18	3.19	1.45	1.43								12.046	6.707	2256	2288	12.1	12.2
80% FA		2.2575	1.25	2241	31.2	3.21		1.4									11.776	6.57	2262	2292	12.2	
		2.2185	1.22	2222	31.5	3.17		1.45														
	3	2.2445	1.2435	2242	25.8	3.88	3.88	3.5	3.58								12.1065	6.744	2258	2936	20.0	20.0
		2.2395	1.2385	2237	25.8	3.88		3.75									11.833	6.613	2267	2934	20.1	
		2.255	1.241	2224	25.8	3.88		3.5														
	7	2.184	1.194	2206	25.7	3.89	3.89	5	4.92							7548	12.079	6.726	2256	3000	20.9	21.2
		2.2315	1.2215	2209	25.8	3.88		5.05									11.832	6.607	2264	3034	21.4	
		2.261	1.25	2236	25.7	3.89		4.7														
	28	2.2335	1.235	2237	24.5	4.08	4.14	7.55	7.57	3.4835	1.915	2221	36	1.15	1.11	4560	12.107	6.751	2260	3200	23.8	24.2
		2.2365	1.2335	2230	24.1	4.15		7		3.5405	1.98	2269	28.5	0.91			11.857	6.628	2268	3245	24.6	
		2.316	1.2925	2263	23.8	4.20		8.15		3.4965	1.952	2264	40	1.27								
	56	2.23	1.235	2241	23.8	4.20	4.21	11.05	10.85								12.105	6.755	2263	3383	26.6	26.9
		2.235	1.225	2213	23.8	4.20		10.85									11.8545	6.629	2269	3414	27.2	
		2.307	1.288	2264	23.7	4.22		10.65														
	91	2.1965	1.225	2261	23.4	4.27	4.27	13.2	14.28	3.48	1.934	2251	62.5	1.99	2.04	3205	12.12	6.768	2265	3482	28.2	28.4
		2.2645	1.2555	2244	23.4	4.27		15.65		3.5405	1.98	2269	63.5	2.02			11.8695	6.6435	2271	3500	28.6	
		2.2675	1.2665	2265	23.4	4.27		14		3.558	1.99	2269	66.5	2.12								
13	1	2.3225	1.311	2296	22.8	4.39	4.39	14.75	13.95								11.748	6.575	2271	3580	29.1	28.9
TB		2.3665	1.36	2351	23	4.35		13.7									11.787	6.519	2237	3580	28.7	

Appendix 6 Tabulated Results – Hardened Concrete Properties

20% GGBS		2.3645	1.349	2328	22.5	4.44		13.4														
	3	2.4045	1.372	2329	21.8	4.59	4.59	32.85	31.10								11.846	6.739	2320	4058	38.2	38.1
		2.3625	1.3535	2341	21.7	4.61		31.45									11.8675	6.763	2325	4045	38.0	
		2.3805	1.37	2356	21.8	4.59		29														
	7	2.402	1.389	2371	21.1	4.74	4.74	39.35	40.13							7257	11.861	6.828	2357	4210	41.8	41.7
		2.3105	1.381	2486	21.1	4.74		38.95									11.886	6.81	2342	4213	41.6	
		2.36	1.362	2365	21.1	4.74		42.1														
	28	2.392	1.382	2368	20.8	4.81	4.81	55.45	54.08	3.683	2.123	2361	174	5.54	5.09	3491	11.868	6.841	2361	4415	46.0	45.9
		2.3505	1.3595	2372	20.8	4.81		50.75		3.7055	2.1275	2348	150.5	4.79			11.89	6.845	2357	4404	45.7	
		2.371	1.375	2381	20.8	4.81		56.05		3.6775	2.11	2346	155	4.93								
	56	2.3605	1.3665	2375	20.4	4.90	4.90	68.75	70.80								11.8935	6.855	2361	4458	46.9	46.9
		2.385	1.376	2364	20.4	4.90		70.07									11.905	6.855	2357	4460	46.9	
		2.3975	1.3855	2369	20.4	4.90		73.57														
	91	2.37	1.37	2370	20.3	4.93	4.93	75.6	76.56	3.7005	2.1325	2360	168.5	5.36	5.72	2347	11.905	6.86	2360	4500	47.8	47.5
		2.396	1.386	2372	20.3	4.93		79.49		3.6615	2.0985	2343	177.1	5.64			11.9145	6.864	2359	4478	47.3	
		2.416	1.408	2397	20.3	4.93		74.59		3.6295	2.0625	2316	193.6	6.16								
14	1	2.3195	1.325	2332	24.4	4.10	4.12	7.7	7.80								11.5515	6.6255	2345	3295	25.5	25.7
TB		2.357	1.352	2345	24.4	4.10		8.6									11.579	6.64	2344	3325	25.9	
40% GGBS		2.3125	1.323	2337	24.1	4.15		7.1														
	3	2.34	1.345	2352	21.6	4.63	4.60	26.25	25.97								11.6445	6.7045	2357	4018	38.1	38.3
		2.387	1.371	2349	21.8	4.59		25.15									11.656	6.7145	2359	4046	38.6	
		2.376	1.363	2346	21.8	4.59		26.5														
	7	2.3525	1.3515	2350	21.5	4.65	4.65	36.2	38.63							2237	11.6535	6.72	2362	4214	41.9	42.2
		2.411	1.39	2361	21.5	4.65		38.15									11.676	6.724	2358	4247	42.5	
		2.3685	1.3585	2345	21.5	4.65		41.55														
	28	2.3315	1.3375	2346	20.9	4.78	4.79	58.3	54.27	3.6885	2.1235	2357	142.5	4.54	4.88	1448	11.67	6.733	2364	4422	46.2	46.6

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2.384	1.371	2353	20.9	4.78		53.35		3.684	2.12	2355	181	5.76			11.69	6.74	2362	4459	47.0	
		2.3815	1.3675	2349	20.8	4.81		51.15		3.6815	2.1045	2334	136.5	4.34								
	56	2.352	1.361	2373	20.6	4.85	4.85	71.68	70.22								11.6825	6.741	2364	4495	47.8	48.1
		2.3905	1.3815	2369	20.6	4.85		66.95									11.698	6.747	2363	4525	48.4	
		2.3685	1.365	2360	20.6	4.85		72.03														
	91	2.349	1.339	2326	20.2	4.950	4.94	73.75	73.29	3.7075	2.145	2373	162.9	5.19	5.08	990	11.6925	6.744	2363	4520	48.3	48.5
		2.3425	1.3505	2361	20.2	4.950		73.13		3.662	2.1	2344	154.6	4.92			11.707	6.75	2362	4540	48.7	
		2.389	1.373	2351	20.3	4.926		72.98		3.723	2.149	2365	161.1	5.13								
15	1	2.3145	1.318	2323	24.8	4.03	4.02	6.05	5.83								11.399	6.486	2320	2938	20.0	20.4
TB		2.3325	1.335	2338	24.9	4.02		5.95									11.4635	6.5315	2324	2994	20.8	
60% GGBS		2.334	1.337	2341	24.9	4.02		5.5														
	3	2.324	1.323	2322	22.6	4.42	4.44	21.9	22.22								11.5	6.569	2332	3895	35.4	35.7
		2.389	1.367	2338	22.5	4.44		22.35									11.565	6.616	2337	3923	36.0	
		2.3395	1.3385	2337	22.5	4.44		22.4														
	7	2.3935	1.37	2339	21.5	4.65	4.67	36.05	34.72							829	11.507	6.579	2335	4097	39.2	39.4
		2.3535	1.3515	2349	21.4	4.67		33.35									11.567	6.626	2341	4108	39.5	
		2.34	1.34	2340	21.4	4.67		34.75														
	28	2.3375	1.3435	2352	20.9	4.78	4.78	48.85	49.23	3.616	2.059	2322	136	4.33	4.46	573.2	11.52	6.59	2337	4312	43.4	43.6
		2.357	1.355	2352	20.9	4.78		47.7		3.5975	2.02	2281	144	4.58			11.58	6.637	2343	4320	43.7	
		2.374	1.366	2355	20.9	4.78		51.15		3.6225	2.06	2318	140	4.46								
	56	2.359	1.358	2357	20.8	4.81	4.82	56.4	60.29								11.526	6.598	2339	4378	44.8	45.0
		2.344	1.343	2342	20.7	4.83		62.71									11.5885	6.642	2343	4390	45.2	
		2.379	1.372	2362	20.7	4.83		61.75														
	91	2.326	1.333	2342	20.5	4.88	4.88	59.87	62.72	3.572	2.038	2329	146.5	4.66	4.76	446	11.535	6.6	2337	4406	45.4	45.4
		2.362	1.354	2343	20.5	4.88		63.12		3.531	2.023	2342	141	4.49			11.599	6.648	2343	4406	45.5	

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2.345	1.3445	2344	20.5	4.88		65.18		3.651	2.085	2331	160.9	5.12								
16	1	2.3565	1.3385	2315	29.7	3.37	3.37	3.25	3.27								11.4795	6.5185	2314	2474	14.2	14.8
TB		2.3355	1.329	2320	29.7	3.37		3.05									11.3725	6.4845	2327	2580	15.5	
80% GGBS		2.314	1.324	2337	29.5	3.39		3.5														
	3	2.3385	1.3365	2334	22.7	4.41	4.41	19.4	18.97								11.561	6.583	2322	3806	33.6	34.2
		2.3375	1.3415	2347	22.6	4.42		18.55									11.4445	6.5445	2336	3856	34.7	
		2.3645	1.354	2340	22.7	4.41		18.95														
	7	2.33	1.341	2356	22.2	4.50	4.51	30.45	29.72							370.7	11.563	6.589	2325	3940	36.1	36.6
		2.335	1.335	2335	22.2	4.50		30.4									11.4515	6.552	2337	3987	37.2	
		2.335	1.34	2347	22.1	4.52		28.3														
	28	2.3355	1.3365	2338	21.8	4.59	4.59	42.47	42.01	3.6975	2.118	2341	135.1	4.30	4.10	362.3	11.5815	6.5985	2324	4174	40.5	40.9
		2.3775	1.365	2348	21.8	4.59		41.54		3.6985	2.125	2350	124.2	3.95			11.4635	6.558	2337	4200	41.2	
		2.3945	1.3775	2354	21.8	4.59		42.02		3.7035	2.11	2324	127	4.04								
	56	2.3425	1.3425	2343	21.1	4.74	4.74	50.53	49.47								11.5845	6.6055	2327	4239	41.8	42.3
		2.316	1.309	2300	21.1	4.74		45.76									11.4685	6.5655	2339	4275	42.7	
		2.362	1.357	2350	21.1	4.74		52.13														
	91	2.3645	1.3475	2325	20.9	4.78	4.79	49.54	50.06	3.6855	2.1195	2353	147.3	4.69	4.76	227	11.5905	6.6025	2324	4260	42.2	42.6
		2.273	1.277	2282	20.9	4.78		49.73		3.681	2.108	2340	153.2	4.88			11.474	6.565	2337	4295	43.1	
		2.3515	1.3445	2335	20.8	4.81		50.9		3.6845	2.1135	2345	147.8	4.70								
17	1	2.3825	1.3635	2338	23.6	4.24	4.26	13.8	14.43								11.6	6.661	2349	3615	30.7	30.9
TB		2.35	1.35	2350	23.4	4.27		14.95									11.785	6.763	2347	3644	31.2	
20% FA		2.292	1.3	2310	23.5	4.26		14.55														
	3	2.3695	1.3635	2355	21.6	4.63	4.63	35.8	33.42								11.6945	6.745	2363	4140	40.5	40.6
		2.352	1.349	2345	21.6	4.63		31.35									11.878	6.855	2365	4148	40.7	
		2.3555	1.35	2343	21.6	4.63		33.1														

Appendix 6 Tabulated Results – Hardened Concrete Properties

	7	2.354	1.354	2354	21.4	4.67	4.67	36.8	38.45							9821	11.715	6.757	2363	4280	43.3	43.3
		2.3225	1.3205	2318	21.5	4.65		35.2									11.8975	6.864	2364	4280	43.3	
		2.3825	1.3815	2380	21.4	4.67		43.35														
	28	2.3985	1.396	2393	20.9	4.78	4.78	66.26	65.47	3.7015	2.144	2377	129.5	4.12	4.25	1839	11.733	6.783	2370	4444	46.8	46.7
		2.408	1.395	2377	20.9	4.78		68.2		3.61	2.075	2352	136	4.33			11.922	6.876	2363	4440	46.6	
		2.381	1.376	2369	20.9	4.78		61.94		3.711	2.144	2368	135	4.30								
	56	2.345	1.34	2333	20.7	4.83	4.84	67.2	68.14								11.747	6.79	2370	4480	47.6	47.7
		2.352	1.343	2331	20.7	4.83		66.57									11.927	6.898	2372	4490	47.8	
		2.397	1.387	2373	20.6	4.85		70.65														
	91	2.3835	1.3785	2372	20.3	4.93	4.91	73.78	73.49	3.6885	2.1245	2358	186.4	5.93	5.53	1223	11.7545	6.7995	2372	4546	49.0	49.0
		2.374	1.361	2344	20.4	4.90		73.58		3.671	2.117	2362	165.8	5.28			11.931	6.9	2371	4545	49.0	
		2.375	1.365	2351	20.4	4.90		73.12		3.6775	2.1075	2342	169.3	5.39								
18	1	2.285	1.28	2274	25.9	3.86	3.83	6.7	6.27								11.447	6.52	2323	3213	24.0	23.0
TB		2.243	1.252	2263	26	3.85		6.35									11.537	6.516	2298	3092	22.0	
40% FA		2.262	1.269	2278	26.4	3.79		5.75														
	3	2.282	1.273	2262	23.5	4.26	4.28	19.5	18.33								11.529	6.582	2331	3858	34.7	33.5
		2.318	1.316	2313	23.3	4.29		17.15									11.621	6.581	2306	3745	32.3	
		2.302	1.297	2291	23.3	4.29		18.35														
	7	2.3375	1.321	2300	22.5	4.44	4.44	23.2	25.02							9454	11.5435	6.596	2333	3985	37.1	35.9
		2.3345	1.3265	2316	22.5	4.44		25.97									11.6445	6.6	2308	3883	34.8	
		2.3225	1.311	2296	22.5	4.44		25.88														
	28	2.356	1.336	2310	21.5	4.65	4.65	42.7	41.82	3.642	2.065	2309	88.5	2.82	3.31	1903	11.563	6.618	2338	4225	41.7	40.6
		2.2755	1.285	2297	21.5	4.65		40.35		3.6305	2.06	2312	115.5	3.68			11.661	6.623	2315	4132	39.5	
		2.336	1.325	2311	21.5	4.65		42.41		3.616	2.042	2297	107.9	3.43								
	56	2.349	1.332	2310	21.3	4.69	4.69	49.27	47.99								11.575	6.6265	2339	4315	43.6	42.3
		2.2985	1.3075	2319	21.3	4.69		46.4									11.675	6.63	2314	4213	41.1	

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2.3155	1.319	2324	21.3	4.69		48.31														
	91	2.2965	1.305	2316	21.1	4.74	4.72	50.3	51.20	3.6405	2.068	2315	111.6	3.55	4.08	951	11.5815	6.6295	2339	4380	44.9	43.8
		2.34	1.325	2305	21.2	4.72		53.23		3.612	2.0425	2301	141.4	4.50			11.68	6.634	2315	4297	42.7	
		2.3315	1.3255	2318	21.2	4.72		50.08		3.677	2.101	2333	131.8	4.20								
19	1	2.198	1.206	2216	30.6	3.27	3.27	1.99	2.04								11.181	6.224	2256	2260	11.5	12.6
TB		2.1955	1.2075	2222	30.6	3.27		2.14									11.155	6.199	2251	2470	13.7	
60% FA		2.246	1.249	2253	30.6	3.27		1.99														
	3	2.249	1.254	2260	25	4.00	4.01	8.5	8.42								11.237	6.271	2263	3309	24.8	25.3
		2.202	1.216	2233	24.9	4.02		8.32									11.22	6.236	2251	3392	25.9	
		2.242	1.244	2246	25	4.00		8.45														
	7	2.313	1.2985	2280	22.8	4.39	4.37	12.1	12.16							10570	11.2545	6.2885	2266	3515	28.0	28.4
		2.282	1.266	2246	22.8	4.39		12.53									11.2405	6.2585	2256	3572	28.8	
		2.225	1.226	2227	23.1	4.33		11.85														
	28	2.303	1.296	2287	22.3	4.48	4.48	25.54	25.62	3.521	1.947	2237	92.5	2.94	2.92	2750	11.2855	6.3185	2272	3850	33.7	34.2
		2.2725	1.2655	2257	22.3	4.48		25.19		3.5235	1.952	2242	93.4	2.97			11.272	6.288	2262	3918	34.7	
		2.3235	1.3125	2298	22.3	4.48		26.12		3.5795	2.004	2272	89.6	2.85								
	56	2.246	1.254	2264	22.1	4.52	4.52	30.81	31.02								11.3015	6.3245	2271	3995	36.2	36.6
		2.2935	1.2835	2271	22.1	4.52		31.83									11.274	6.296	2265	4040	37.0	
		2.225	1.23	2236	22.1	4.52		30.42														
	91	2.335	1.327	2316	21.6	4.63	4.63	35.19	34.56	3.491	1.935	2244	110.7	3.52	3.97	1009	11.309	6.328	2270	4053	37.3	37.5
		2.245	1.249	2254	21.6	4.63		33.92		3.5865	2.0135	2280	128.5	4.09			11.277	6.305	2268	4081	37.8	
		2.29	1.289	2288	21.6	4.63		34.56		3.535	1.956	2239	135	4.30								
20	1	2.2235	1.2305	2239	37.5	2.67	2.65	0.61	0.58								11.011	6.095	2240	1808	7.3	7.3
TB		2.1615	1.1575	2153	37.8	2.65		0.6														
80% FA		2.2235	1.2165	2208	37.9	2.64		0.53														

Appendix 6 Tabulated Results – Hardened Concrete Properties

	3	2.285	1.2675	2246	27.4	3.65	3.65	2.08	2.10								11.063	6.13	2243	2414	13.1	13.1
		2.251	1.2385	2223	27.5	3.64		2.13														
		2.1995	1.1905	2180	27.3	3.66		2.1														
	7	2.177	1.178	2179	26.9	3.72	3.72	3.28	3.13							11500	11.07	6.143	2247	2680	16.1	16.1
		2.234	1.219	2201	26.9	3.72		2.95														
		2.2205	1.2145	2207	26.9	3.72		3.17														
	28	2.2325	1.225	2216	26.1	3.83	3.84	6.5	6.70	3.4315	1.8735	2203	27.5	0.88	0.86	3290	11.096	6.168	2252	3055	21.0	21.0
		2.229	1.22	2209	26.1	3.83		7.14		3.4735	1.9045	2214	27.1	0.86								
		2.2715	1.2535	2231	26	3.85		6.47		3.4875	1.9205	2226	26.1	0.83								
	56	2.285	1.27	2251	24.4	4.10	4.10	9.26	9.14								11.1135	6.182	2254	3160	22.5	22.5
		2.2395	1.2385	2237	24.4	4.10		8.86														
		2.231	1.233	2235	24.4	4.10		9.31														
	91	2.233	1.223	2211	24.2	4.13	4.14	10.31	10.21	3.446	1.882	2203	37.3	1.19	1.38	2878	11.1215	6.192	2256	3200	23.1	23.1
		2.268	1.256	2241	24.1	4.15		10.43		3.4915	1.9195	2221	41	1.31								
		2.215	1.225	2237	24.2	4.13		9.9		3.554	1.988	2269	51.9	1.65								

A6. 2 *Flowing concrete*

Table A6-2 Tabulated results for flowing concrete

Test Specimen		Cubes								Cylinders							Prisms					
Mix No	Age	Weight (Air)	Weight (Water)	Density	UPV	UPV	Avg. UPV	Compressive Strength	Avg. Compressive Strength	Weight (Air)	Weight (Water)	Density	Load	Splitting Strength	Avg. Splitting Strength	RCPT Charge Passed (Coloumbs)	Weight (Air)	Weight (Water)	Density	Natural frequency	E_d	Avg. E_d
	(days)	(kg)	(kg)	(kg/m^3)	Time	(km/s)	(km/s)	(MPa)	(Mpa)	(kg)	(kg)	(kg/m^3)	(kN)	(MPa)	(Mpa)		(kg)	(kg)	(kg/m^3)	(Hz)	(Gpa)	(Gpa)
21	1	2376.5	1364.5	2348	22.4	4.46	4.46	23.56	23.10								11869	6840	2360	3850	35.0	34.4
Control		2378	1362	2341	22.4	4.46		22.98									11822	6776	2343	3800	33.8	
Mix		2399	1386	2368	22.4	4.46		22.75														
	3	2363.5	1365.5	2368	21.5	4.65	4.67	38.49	40.05								11937	6877	2359	4165	40.9	40.3
		2359	1364	2371	21.4	4.67		41.74									11893	6832	2350	4110	39.7	
		2410	1395.5	2376	21.4	4.67		39.92														
	7	2396.5	1381.5	2361	21	4.76	4.76	47.49	47.47							6645	11954.5	6891.5	2361	4265	42.9	42.3
		2368.5	1370	2372	21	4.76		47.26									11905	6850	2355	4210	41.7	
		2411.5	1396.5	2376	21	4.76		47.67														
	28	2387.5	1380	2370	20.6	4.85	4.85	59.8	55.94	3.73	2.15	2358	126	4.00	4.04	2700	11968.5	6903.5	2363	4365	45.0	44.5
		2369	1365	2360	20.6	4.85		53.57		3.71	2.14	2356	124	3.95			11922.5	6864.5	2357	4320	44.0	
		2427.5	1405	2374	20.6	4.85		54.45		3.70	2.12	2351	131	4.15								
	56	2404	1392	2375	20.4	4.90	4.90	61.64	62.09								11983	6914	2364	4398	45.7	45.3
		2443	1415	2376	20.4	4.90		63.14									11934	6875	2359	4362	44.9	
		2395	1382	2364	20.4	4.90		61.5														
	91	2374.5	1359.5	2339	20.3	4.93	4.93	65.56	65.94	3.7515	2.1655	2365	146.4	4.66	4.30	1980	11987	6918	2365	4421	46.2	45.8
		2393.5	1378.5	2358	20.3	4.93		66.91		3.73	2.153	2365	136.5	4.34			11943	6880	2359	4390	45.5	

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2446	1420	2384	20.3	4.93		65.36		3.723	2.147	2362	122.6	3.90								
22	1	2352.5	1349.5	2345	23.2	4.31	4.29	14.97	15.05								11757	6750	2348	3680	31.8	31.5
20% LP		2320	1318	2315	23.4	4.27		15.51									11681	6709	2349	3640	31.1	
		2307	1310	2314	23.4	4.27		14.66														
	3	2370	1363	2354	21.6	4.63	4.62	29.06	29.62								11831	6806	2354	4060	38.8	38.5
		2368	1357	2342	21.6	4.63		29.56									11753	6755	2352	4030	38.2	
		2340	1336	2331	21.7	4.61		30.25														
	7	2352.5	1344.5	2334	21.4	4.67	4.67	39.22	38.40							4106	11843	6818	2357	4197	41.5	41.3
		2355.5	1349	2340	21.4	4.67		36.49									11773	6768	2352	4175	41.0	
		2371.5	1360.5	2346	21.4	4.67		39.49														
	28	2375	1370	2363	20.9	4.78	4.78	45.61	46.63	3.691	2.121	2351	120.3	3.83	3.76	3905	11860	6842	2363	4320	44.1	43.8
		2358	1351	2342	20.9	4.78		48.36		3.653	2.09	2337	112.5	3.58			11786	6782	2355	4295	43.4	
		2357	1351	2343	20.9	4.78		45.92		3.6845	2.1185	2353	121.6	3.87								
	56	2437	1406	2364	20.8	4.81	4.82	49.06	50.60								11862	6842	2363	4355	44.8	44.5
		2341.5	1338.5	2334	20.7	4.83		51.77									11790	6790	2358	4325	44.1	
		2370	1363	2354	20.7	4.83		50.96														
	91	2387	1378	2366	20.6	4.85	4.86	53.71	53.63	3.685	2.106	2334	130.9	4.17	4.15	2655	11864	6845	2364	4385	45.5	45.1
		2339	1348	2360	20.6	4.85		53.14		3.692	2.1165	2343	131.8	4.20			11791	6792	2359	4356	44.8	
		2358	1360	2363	20.5	4.88		54.04		3.698	2.125	2351	128.6	4.09								
23	1	2361	1343	2319	25	4.00	4.02	9.27	9.61								11600	6617	2328	3360	26.3	26.0
40% GGBS		2330	1330	2330	25	4.00		9.5									11588	6616	2331	3320	25.7	
		2300.5	1302.5	2305	24.6	4.07		10.06														
	3	2369	1353	2332	22.1	4.52	4.52	23.8	24.07								11700	6697	2339	3900	35.6	35.6
		2374	1366	2355	22.1	4.52		23.24									11706.5	6711	2343	3900	35.6	
		2355	1345	2332	22.1	4.52		25.17														

Appendix 6 Tabulated Results – Hardened Concrete Properties

	7	2374	1365	2353	21.7	4.61	4.60	36.47	36.04							2596	11715	6715	2343	4038	38.2	38.3
		2350	1343	2334	21.8	4.59		35.6									11719	6730	2349	4040	38.3	
		2357	1349	2338	21.7	4.61		36.06														
	28	2363.5	1362.5	2361	21.1	4.74	4.75	51.49	51.43	3.6965	2.1255	2353	128.2	4.08	4.04	1175	11740.5	6737.5	2347	4230	42.0	42.1
		2366.5	1365	2363	21.1	4.74		50.4		3.7105	2.1355	2356	125.4	3.99			11732	6751	2355	4230	42.1	
		2404	1380	2348	21	4.76		52.41		3.714	2.137	2355	126.8	4.04								
	56	2329.5	1329.5	2330	20.8	4.81	4.81	57.55	56.10								11745.5	6741.5	2347	4326	43.9	44.0
		2333	1339	2347	20.8	4.81		55.61									11737	6757	2357	4326	44.1	
		2397	1383	2364	20.8	4.81		55.13														
	91	2376.5	1369	2359	20.7	4.83	4.85	59.37	59.92	3.701	2.13	2356	135.5	4.31	4.37	900	11747.5	6743	2347	4398	45.4	45.4
		2406.5	1388.5	2364	20.6	4.85		60.43		3.657	2.095	2341	139.3	4.43			11744.5	6761	2357	4388	45.4	
		2385	1374	2359	20.6	4.85		59.97		3.7205	2.132	2342	136.8	4.35								
24	1	2275.5	1286	2300	24.4	4.10	4.10	10.16	9.55								11203	6258	2266	3240	23.8	23.2
20% FA		2300	1296	2291	24.3	4.12		9.67									11254.5	6266.5	2256	3160	22.5	
		2284	1278	2270	24.4	4.10		8.81														
	3	2287	1292	2298	22.3	4.48	4.47	22.09	21.51								11323	6354	2279	3800	32.9	32.5
		2251	1262	2276	22.4	4.46		20.9									11364	6359	2271	3760	32.1	
		2255	1263	2273	22.4	4.46		21.55														
	7	2312	1307	2300	21.5	4.65	4.67	27.78	28.22							5956	11340	6377	2285	3960	35.8	35.5
		2262	1273	2287	21.4	4.67		28.94									11379	6383	2278	3925	35.1	
		2299.5	1292	2282	21.4	4.67		27.95														
	28	2312.5	1310.5	2308	21.2	4.72	4.71	38.46	38.30	3.5695	2.01	2289	94.3	3.00	3.11	4180	11359	6389	2286	4080	38.0	37.7
		2298	1290	2280	21.2	4.72		38.7		3.513	1.97	2277	101.6	3.23			11400.5	6395.5	2278	4045	37.3	
		2252	1265	2282	21.3	4.69		37.74		3.5845	2.028	2303	97.5	3.10								
	56	2275.5	1278.5	2282	21.1	4.74	4.75	43.47	43.90								11370.5	6398.5	2287	4155	39.5	39.0

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2308.5	1302.5	2295	21.1	4.74		43.55									11410.5	6406.5	2280	4110	38.5	
		2234.5	1316.5	2434	21	4.76		44.67														
	91	2317.5	1316	2314	20.9	4.78	4.79	48.63	47.88	3.5645	1.998	2275	121.8	3.88	3.90	1000	11381.5	6409	2289	4220	40.8	40.3
		2287.5	1285	2282	20.9	4.78		47.15		3.6115	2.0455	2306	120.6	3.84			11415	6415	2283	4182	39.9	
		2297.5	1303	2310	20.8	4.81		47.87		3.5565	1.993	2275	124.7	3.97								
25	1	2327	1323	2318	24.5	4.08	4.06	7.43	7.30								11685	6626	2310	3155	23.0	22.6
TB		2335	1328	2319	24.7	4.05		6.99									11632	6599	2311	3100	22.2	
40% GGBS		2314	1315	2316	24.7	4.05		7.47														
	3	2335	1325	2312	22.6	4.42	4.42	16.76	18.40								11778.5	6703.5	2321	3780	33.2	33.1
		2361	1348	2331	22.6	4.42		18.88									11741	6697	2328	3765	33.0	
		2382	1358	2326	22.6	4.42		19.56														
	7	2380	1360	2333	21.8	4.59	4.57	26.99	27.32							1330	11792.5	6720.5	2325	3980	36.8	36.8
		2349.5	1335	2316	21.8	4.59		27.57									11756	6715.5	2332	3970	36.8	
		2338	1328	2315	22.0	4.55		27.4														
	28	2344.5	1330	2311	21.5	4.65	4.65	44.24	42.68	3.672	2.1	2336	119.2	3.79	3.60	1188	11806.5	6734.5	2328	4205	41.2	41.0
		2376.5	1360	2338	21.5	4.65		42.33		3.672	2.1	2336	111.7	3.56			11769.5	6727.5	2334	4185	40.9	
		2373.5	1356	2333	21.5	4.65		41.48		3.6775	2.1045	2338	108.4	3.45								
	56	2376	1350	2316	21.1	4.74	4.73	48.26	48.39								11806.5	6740.5	2331	4290	42.9	42.7
		2357	1346	2331	21.1	4.74		48.71									11784	6735	2334	4270	42.6	
		2354.5	1332.5	2304	21.2	4.72		48.21														
	91	2395	1369	2334	21	4.76	4.76	49.84	50.40	3.672	2.098	2333	129.8	4.13	4.18	508	11813	6752	2334	4345	44.1	43.8
		2377	1364	2346	21	4.76		50.34		3.662	2.0895	2329	128.6	4.09			11778	6738	2337	4317	43.6	
		2346	1343	2339	21	4.76		51.01		3.646	2.082	2331	135.3	4.31								
26	1	2341.5	1315.5	2282	25.7	3.89	3.92	8.25	8.02								11367	6381	2280	3230	23.8	23.4
TB		2312.5	1300	2284	25.5	3.92		8.69									11272	6305	2269	3180	22.9	

Appendix 6 Tabulated Results – Hardened Concrete Properties

20% FA		2316	1300	2280	25.4	3.94		7.13														
	3	2311.5	1294	2272	23.8	4.20	4.22	18.66	18.52								11433.5	6438.5	2289	3745	32.1	31.6
		2298.5	1290	2279	23.6	4.24		18.11									11345.5	6352.5	2272	3705	31.2	
		2278.5	1269	2257	23.7	4.22		18.8														
	7	2318	1304	2286	22.6	4.42	4.45	24.84	25.40							2700	11455	6456	2291	3912	35.1	34.6
		2395	1364	2323	22.4	4.46		25.38									11355.5	6377.5	2281	3865	34.1	
		2344	1322	2294	22.4	4.46		25.98														
	28	2362	1334	2298	22.1	4.52	4.53	34.18	34.54	3.61	2.033	2289	101.5	3.23	3.48	1589	11468	6468	2294	4035	37.3	36.9
		2391.5	1361.5	2322	22	4.55		34.5		3.58	2.009	2279	114.6	3.65			11373	6384	2280	4000	36.5	
		2342.5	1322.5	2297	22.1	4.52		34.94		3.5625	2.0025	2284	111.9	3.56								
	56	2313.5	1313.5	2314	21.7	4.61	4.62	39.99	39.75								11475	6479	2297	4120	39.0	38.7
		2332.5	1335.5	2340	21.6	4.63		38.09									11384.5	6398	2283	4100	38.4	
		2364	1360	2355	21.6	4.63		41.17														
	91	2374	1348	2314	21.3	4.69	4.71	44.47	44.07	3.6065	2.012	2262	122.3	3.89	3.94	480	11476	6480	2297	4192	40.4	39.9
		2323	1320	2316	21.3	4.69		43.34		3.5765	2.0355	2321	125.1	3.98			11381.5	6399	2284	4150	39.3	
		2350.5	1340	2326	21.1	4.74		44.41		3.6045	2.028	2286	124.2	3.95								
21	1	2376.5	1364.5	2348	22.4	4.46	4.46	23.56	23.10								11869	6840	2360	3850	35.0	34.4
Control		2378	1362	2341	22.4	4.46		22.98									11822	6776	2343	3800	33.8	
Mix		2399	1386	2368	22.4	4.46		22.75														
	3	2363.5	1365.5	2368	21.5	4.65	4.67	38.49	40.05								11937	6877	2359	4165	40.9	40.3
		2359	1364	2371	21.4	4.67		41.74									11893	6832	2350	4110	39.7	
		2410	1395.5	2376	21.4	4.67		39.92														
	7	2396.5	1381.5	2361	21	4.76	4.76	47.49	47.47							6645	11954.5	6891.5	2361	4265	42.9	42.3
		2368.5	1370	2372	21	4.76		47.26									11905	6850	2355	4210	41.7	
		2411.5	1396.5	2376	21	4.76		47.67														
	28	2387.5	1380	2370	20.6	4.85	4.85	59.8	55.94	3.73	2.15	2358	126	4.00	4.04	2700	11968.5	6903.5	2363	4365	45.0	44.5

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2369	1365	2360	20.6	4.85		53.57		3.71	2.14	2356	124	3.95			11922.5	6864.5	2357	4320	44.0	
		2427.5	1405	2374	20.6	4.85		54.45		3.70	2.12	2351	131	4.15								
	56	2404	1392	2375	20.4	4.90	4.90	61.64	62.09								11983	6914	2364	4398	45.7	45.3
		2443	1415	2376	20.4	4.90		63.14									11934	6875	2359	4362	44.9	
		2395	1382	2364	20.4	4.90		61.5														
	91	2374.5	1359.5	2339	20.3	4.93	4.93	65.56	65.94	3.7515	2.1655	2365	146.4	4.66	4.30	1980	11987	6918	2365	4421	46.2	45.8
		2393.5	1378.5	2358	20.3	4.93		66.91		3.73	2.153	2365	136.5	4.34			11943	6880	2359	4390	45.5	
		2446	1420	2384	20.3	4.93		65.36		3.723	2.147	2362	122.6	3.90								
22	1	2352.5	1349.5	2345	23.2	4.31	4.29	14.97	15.05								11757	6750	2348	3680	31.8	31.5
20% LP		2320	1318	2315	23.4	4.27		15.51									11681	6709	2349	3640	31.1	
		2307	1310	2314	23.4	4.27		14.66														
	3	2370	1363	2354	21.6	4.63	4.62	29.06	29.62								11831	6806	2354	4060	38.8	38.5
		2368	1357	2342	21.6	4.63		29.56									11753	6755	2352	4030	38.2	
		2340	1336	2331	21.7	4.61		30.25														
	7	2352.5	1344.5	2334	21.4	4.67	4.67	39.22	38.40							4106	11843	6818	2357	4197	41.5	41.3
		2355.5	1349	2340	21.4	4.67		36.49									11773	6768	2352	4175	41.0	
		2371.5	1360.5	2346	21.4	4.67		39.49														
	28	2375	1370	2363	20.9	4.78	4.78	45.61	46.63	3.691	2.121	2351	120.3	3.83	3.76	3905	11860	6842	2363	4320	44.1	43.8
		2358	1351	2342	20.9	4.78		48.36		3.653	2.09	2337	112.5	3.58			11786	6782	2355	4295	43.4	
		2357	1351	2343	20.9	4.78		45.92		3.6845	2.1185	2353	121.6	3.87								
	56	2437	1406	2364	20.8	4.81	4.82	49.06	50.60								11862	6842	2363	4355	44.8	44.5
		2341.5	1338.5	2334	20.7	4.83		51.77									11790	6790	2358	4325	44.1	
		2370	1363	2354	20.7	4.83		50.96														
	91	2387	1378	2366	20.6	4.85	4.86	53.71	53.63	3.685	2.106	2334	130.9	4.17	4.15	2655	11864	6845	2364	4385	45.5	45.1
		2339	1348	2360	20.6	4.85		53.14		3.692	2.1165	2343	131.8	4.20			11791	6792	2359	4356	44.8	

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2358	1360	2363	20.5	4.88		54.04		3.698	2.125	2351	128.6	4.09								
23	1	2361	1343	2319	25	4.00	4.02	9.27	9.61								11600	6617	2328	3360	26.3	26.0
40% GGBS		2330	1330	2330	25	4.00		9.5									11588	6616	2331	3320	25.7	
		2300.5	1302.5	2305	24.6	4.07		10.06														
	3	2369	1353	2332	22.1	4.52	4.52	23.8	24.07								11700	6697	2339	3900	35.6	35.6
		2374	1366	2355	22.1	4.52		23.24									11706.5	6711	2343	3900	35.6	
		2355	1345	2332	22.1	4.52		25.17														
	7	2374	1365	2353	21.7	4.61	4.60	36.47	36.04							2596	11715	6715	2343	4038	38.2	38.3
		2350	1343	2334	21.8	4.59		35.6									11719	6730	2349	4040	38.3	
		2357	1349	2338	21.7	4.61		36.06														
	28	2363.5	1362.5	2361	21.1	4.74	4.75	51.49	51.43	3.6965	2.1255	2353	128.2	4.08	4.04	1175	11740.5	6737.5	2347	4230	42.0	42.1
		2366.5	1365	2363	21.1	4.74		50.4		3.7105	2.1355	2356	125.4	3.99			11732	6751	2355	4230	42.1	
		2404	1380	2348	21	4.76		52.41		3.714	2.137	2355	126.8	4.04								
	56	2329.5	1329.5	2330	20.8	4.81	4.81	57.55	56.10								11745.5	6741.5	2347	4326	43.9	44.0
		2333	1339	2347	20.8	4.81		55.61									11737	6757	2357	4326	44.1	
		2397	1383	2364	20.8	4.81		55.13														
	91	2376.5	1369	2359	20.7	4.83	4.85	59.37	59.92	3.701	2.13	2356	135.5	4.31	4.37	900	11747.5	6743	2347	4398	45.4	45.4
		2406.5	1388.5	2364	20.6	4.85		60.43		3.657	2.095	2341	139.3	4.43			11744.5	6761	2357	4388	45.4	
		2385	1374	2359	20.6	4.85		59.97		3.7205	2.132	2342	136.8	4.35								
24	1	2275.5	1286	2300	24.4	4.10	4.10	10.16	9.55								11203	6258	2266	3240	23.8	23.2
20% FA		2300	1296	2291	24.3	4.12		9.67									11254.5	6266.5	2256	3160	22.5	
		2284	1278	2270	24.4	4.10		8.81														
	3	2287	1292	2298	22.3	4.48	4.47	22.09	21.51								11323	6354	2279	3800	32.9	32.5
		2251	1262	2276	22.4	4.46		20.9									11364	6359	2271	3760	32.1	
		2255	1263	2273	22.4	4.46		21.55														

Appendix 6 Tabulated Results – Hardened Concrete Properties

	7	2312	1307	2300	21.5	4.65	4.67	27.78	28.22							5956	11340	6377	2285	3960	35.8	35.5
		2262	1273	2287	21.4	4.67		28.94									11379	6383	2278	3925	35.1	
		2299.5	1292	2282	21.4	4.67		27.95														
	28	2312.5	1310.5	2308	21.2	4.72	4.71	38.46	38.30	3.5695	2.01	2289	94.3	3.00	3.11	4180	11359	6389	2286	4080	38.0	37.7
		2298	1290	2280	21.2	4.72		38.7		3.513	1.97	2277	101.6	3.23			11400.5	6395.5	2278	4045	37.3	
		2252	1265	2282	21.3	4.69		37.74		3.5845	2.028	2303	97.5	3.10								
	56	2275.5	1278.5	2282	21.1	4.74	4.75	43.47	43.90								11370.5	6398.5	2287	4155	39.5	39.0
		2308.5	1302.5	2295	21.1	4.74		43.55									11410.5	6406.5	2280	4110	38.5	
		2234.5	1316.5	2434	21	4.76		44.67														
	91	2317.5	1316	2314	20.9	4.78	4.79	48.63	47.88	3.5645	1.998	2275	121.8	3.88	3.90	1000	11381.5	6409	2289	4220	40.8	40.3
		2287.5	1285	2282	20.9	4.78		47.15		3.6115	2.0455	2306	120.6	3.84			11415	6415	2283	4182	39.9	
		2297.5	1303	2310	20.8	4.81		47.87		3.5565	1.993	2275	124.7	3.97								
25	1	2327	1323	2318	24.5	4.08	4.06	7.43	7.30								11685	6626	2310	3155	23.0	22.6
TB		2335	1328	2319	24.7	4.05		6.99									11632	6599	2311	3100	22.2	
40% GGBS		2314	1315	2316	24.7	4.05		7.47														
	3	2335	1325	2312	22.6	4.42	4.42	16.76	18.40								11778.5	6703.5	2321	3780	33.2	33.1
		2361	1348	2331	22.6	4.42		18.88									11741	6697	2328	3765	33.0	
		2382	1358	2326	22.6	4.42		19.56														
	7	2380	1360	2333	21.8	4.59	4.57	26.99	27.32							1330	11792.5	6720.5	2325	3980	36.8	36.8
		2349.5	1335	2316	21.8	4.59		27.57									11756	6715.5	2332	3970	36.8	
		2338	1328	2315	22.0	4.55		27.4														
	28	2344.5	1330	2311	21.5	4.65	4.65	44.24	42.68	3.672	2.1	2336	119.2	3.79	3.60	1188	11806.5	6734.5	2328	4205	41.2	41.0
		2376.5	1360	2338	21.5	4.65		42.33		3.672	2.1	2336	111.7	3.56			11769.5	6727.5	2334	4185	40.9	
		2373.5	1356	2333	21.5	4.65		41.48		3.6775	2.1045	2338	108.4	3.45								
	56	2376	1350	2316	21.1	4.74	4.73	48.26	48.39								11806.5	6740.5	2331	4290	42.9	42.7
		2357	1346	2331	21.1	4.74		48.71									11784	6735	2334	4270	42.6	

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2354.5	1332.5	2304	21.2	4.72		48.21														
	91	2395	1369	2334	21	4.76	4.76	49.84	50.40	3.672	2.098	2333	129.8	4.13	4.18	508	11813	6752	2334	4345	44.1	43.8
		2377	1364	2346	21	4.76		50.34		3.662	2.0895	2329	128.6	4.09			11778	6738	2337	4317	43.6	
		2346	1343	2339	21	4.76		51.01		3.646	2.082	2331	135.3	4.31								
26	1	2341.5	1315.5	2282	25.7	3.89	3.92	8.25	8.02								11367	6381	2280	3230	23.8	23.4
TB		2312.5	1300	2284	25.5	3.92		8.69									11272	6305	2269	3180	22.9	
20% FA		2316	1300	2280	25.4	3.94		7.13														
	3	2311.5	1294	2272	23.8	4.20	4.22	18.66	18.52								11433.5	6438.5	2289	3745	32.1	31.6
		2298.5	1290	2279	23.6	4.24		18.11									11345.5	6352.5	2272	3705	31.2	
		2278.5	1269	2257	23.7	4.22		18.8														
	7	2318	1304	2286	22.6	4.42	4.45	24.84	25.40							2700	11455	6456	2291	3912	35.1	34.6
		2395	1364	2323	22.4	4.46		25.38									11355.5	6377.5	2281	3865	34.1	
		2344	1322	2294	22.4	4.46		25.98														
	28	2362	1334	2298	22.1	4.52	4.53	34.18	34.54	3.61	2.033	2289	101.5	3.23	3.48	1589	11468	6468	2294	4035	37.3	36.9
		2391.5	1361.5	2322	22	4.55		34.5		3.58	2.009	2279	114.6	3.65			11373	6384	2280	4000	36.5	
		2342.5	1322.5	2297	22.1	4.52		34.94		3.5625	2.0025	2284	111.9	3.56								
	56	2313.5	1313.5	2314	21.7	4.61	4.62	39.99	39.75								11475	6479	2297	4120	39.0	38.7
		2332.5	1335.5	2340	21.6	4.63		38.09									11384.5	6398	2283	4100	38.4	
		2364	1360	2355	21.6	4.63		41.17														
	91	2374	1348	2314	21.3	4.69	4.71	44.47	44.07	3.6065	2.012	2262	122.3	3.89	3.94	480	11476	6480	2297	4192	40.4	39.9

A6. 3 Underwater concrete

Table A6-3 Tabulated results for underwater concrete

Test Specimen		Cubes								Cylinders							Prisms					
Mix No	Age	Weight (Air)	Weight (Water)	Density	UPV	UPV	Avg. UPV	Compressive Strength	Avg. Compressive Strength	Weight (Air)	Weight (Water)	Density	Load	Splitting Strength	Avg. Splitting Strength	RCPT Charge Passed (Coloumbs)	Weight (Air)	Weight (Water)	Density	Natural frequency	E_d	Avg. E_d
	(days)	(kg)	(kg)	(kg/m^3)	Time	(km/s)	(km/s)	(MPa)	(Mpa)	(kg)	(kg)	(kg/m^3)	(kN)	(MPa)	(Mpa)		(kg)	(kg)	(kg/m^3)	(Hz)	(Gpa)	(Gpa)
27	3	2330	1320	2307	22.1	4.52	4.53	42.36	41.70								11614	6554	2295	3975	36.3	36.3
Control		2336.5	1328.5	2318	22.1	4.52		40									11430	6439	2290	3980	36.3	
Mix		2326.5	1317	2305	22	4.55		42.75														
	7	2292.5	1292	2291	21.8	4.59	4.59	53.76	52.75							10360	11628	6566	2297	4115	38.9	38.9
		2346	1327	2302	21.8	4.59		51.28									11444.5	6453.5	2293	4115	38.8	
		2300	1298	2295	21.8	4.59		53.2														
	28	2352	1332	2306	21.6	4.63	4.63	62.64	61.19	3.61	2.04	2294	152	4.84	4.43	3199	11645.5	6590.5	2304	4225	41.1	41.1
		2329	1321	2311	21.6	4.63		62.13		3.63	2.05	2297	128	4.07			11467	6477	2298	4227	41.1	
		2307.5	1308.5	2310	21.6	4.63		58.81		3.60	2.03	2298	137	4.37								
	28 (Tremie)	2302	1299	2295	21.7	4.61	4.60	53.55	52.73													
		2291.5	1294.5	2298	21.8	4.59		53.58														
		2294	1299	2306	21.7	4.61		51.07														
	56	2300	1295	2289	21.4	4.67	4.67	64.62	63.40								11661.5	6595.5	2302	4270	42.0	41.9

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2353.5	1339.5	2321	21.4	4.67		62.46									11482.5	6485.5	2298	4263	41.8	
		2287.5	1294.5	2304	21.4	4.67		63.11														
	91	2195.5	1245	2310	21.1	4.74	4.77	66.52	65.57	3.55	1.997	2286	160.4	5.11	5.07	2167	11667	6606	2305	4294	42.5	42.5
		2309.5	1318	2329	20.8	4.81		65.02		3.593	2.026	2293	153.8	4.90			11498	6497	2299	4297	42.5	
		2323	1308	2289	21	4.76		65.18		3.6355	2.056	2302	163.7	5.21								
	91 (Tremie)	2187.5	1234	2294	21.5	4.65	4.67	63.54	61.88													
		2269.5	1279	2291	21.4	4.67		59.89														
		2150	1205	2275	21.3	4.69		62.22														
28	3	2300	1297	2293	23.1	4.33	4.33	27.38	28.14								11475	6459	2288	3775	32.6	33.3
20% LP		2321	1303	2280	23.1	4.33		28.64									11559	6535	2301	3849	34.1	
		2320	1303	2281	23.1	4.33		28.4														
	7	2307	1293	2275	22.3	4.48	4.48	35.74	35.02							12500	11487	6474	2291	3935	35.5	36.2
		2305.5	1290.5	2271	22.3	4.48		34.21									11571.5	6551.5	2305	4000	36.9	
		2309	1295	2277	22.3	4.48		35.11														
	28	2330.5	1310.5	2285	21.8	4.59	4.59	41.35	41.88	3.592	2.022	2288	101.6	3.23	3.28	2587	11511	6497	2296	4060	37.8	38.7
		2310	1300	2287	21.8	4.59		42.94		3.5545	1.9935	2277	105.8	3.37			11595	6572	2308	4135	39.5	
		2321	1306	2287	21.8	4.59		41.34		3.5975	2.0215	2283	101.9	3.24								
	28 (Tremie)	2283.5	1286.5	2290	21.8	4.59	4.59	34.65	35.50													
		2310	1296	2278	21.8	4.59		36.04														
		2319.5	1305.5	2287	21.8	4.59		35.81														
	56	2284.5	1286.5	2289	21.6	4.63	4.64	45.34	45.94								11523	6495	2292	4110	38.7	39.5
		2343.5	1328.5	2309	21.5	4.65		47.49									11599	6580	2311	4180	40.4	
		2330.5	1313.5	2292	21.5	4.65		44.98														
	91	2330.5	1316	2297	21.3	4.69	4.72	48.56	47.20	3.6055	2.028	2286	116.8	3.72	3.78	2308	11530.5	6511	2297	4127	39.1	39.9
		2328	1310	2287	21.1	4.74		45.2		3.627	2.042	2288	118.4	3.77			11613.5	6591	2312	4197	40.7	

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2333.5	1318.5	2299	21.2	4.72		47.85		3.615	2.034	2287	121.5	3.87								
	91 (Tremie)	2295	1295.5	2296	21.1	4.74	4.73	41.08	41.60													
		2286.5	1292	2299	21.1	4.74		40.76														
		2322.5	1311.5	2297	21.2	4.72		42.96														
29	3	2334.5	1312.5	2284	23.7	4.22	4.22	21.75	21.48								11362.5	6347.5	2266	3570	28.9	28.7
40% GGBS		2313.5	1295.5	2273	23.7	4.22		20.87									11240.5	6261.5	2258	3560	28.6	
		2287.5	1270.5	2249	23.7	4.22		21.83														
	7	2328	1304	2273	22.9	4.37	4.37	33.36	33.62							4261	11393	6370	2268	3798	32.7	32.7
		2337	1308	2271	22.9	4.37		32.86									11254	6286	2265	3800	32.7	
		2305	1292	2275	22.8	4.39		34.65														
	28	2334.5	1314.5	2289	22.2	4.50	4.50	45.76	44.23	3.5595	1.9935	2273	121.7	3.87	4.09	2106	11402.5	6385.5	2273	3930	35.1	35.1
		2297.5	1281	2260	22.2	4.50		43.32		3.569	1.998	2272	125.2	3.99			11267	6301	2269	3933	35.1	
		2317	1297	2272	22.3	4.48		43.6		3.5505	1.9865	2270	138.5	4.41								
	28 (Tremie)	2287	1277	2264	22.5	4.44	4.44	39.15	37.88													
		2283	1275	2265	22.5	4.44		36.05														
		2290	1280	2267	22.5	4.44		38.45														
	56	2279	1275	2270	22.1	4.52	4.53	48.14	50.42								11410	6391	2273	4130	38.8	38.7
		2268	1276	2286	22.1	4.52		50.03									11268	6302	2269	4130	38.7	
		2312	1301	2287	22	4.55		53.09														
	91	2324	1300	2270	21.6	4.63	4.64	54.72	56.36	3.579	2.002	2269	135.6	4.32	4.50	1602	11410.9	6394	2274	4363	43.3	43.2
		2339	1311	2275	21.5	4.65		56.98		3.5801	2.006	2274	142.6	4.54			11283	6310	2269	4354	43.0	
		2280	1274	2266	21.6	4.63		57.38		3.555	1.99	2272	145.8	4.64								
	91 (Tremie)	2292	1292	2292	21.6	4.63	4.62	46.32	46.96													
		2263	1270	2279	21.7	4.61		45.62														
		2296	1298	2301	21.6	4.63		48.93														

Appendix 6 Tabulated Results – Hardened Concrete Properties

30	3	2305	1292	2275	22.7	4.41	4.42	32.13	32.23								11491	6468	2288	3840	33.7	33.7
20% FA		2344	1321	2291	22.6	4.42		33.68									11531.5	6483.5	2284	3840	33.7	
		2323	1311	2295	22.6	4.42		30.88														
	7	2345.5	1330	2310	21.9	4.57	4.57	38.51	38.51							2660	11504	6467	2284	3965	35.9	35.9
		2347.5	1332	2312	21.8	4.59		39.76									11540	6474	2278	3965	35.8	
		2319	1305	2287	22	4.55		37.26														
	28	2335	1312	2283	21.6	4.63	4.62	48.6	47.64	3.5735	2.0085	2283	121.3	3.86	3.92	1650	11526	6490	2289	4063	37.8	37.9
		2326	1305	2278	21.7	4.61		47.28		3.5845	2.0155	2285	126	4.01			11561	6497	2283	4083	38.1	
		2310	1293	2271	21.7	4.61		47.05		3.568	2.005	2283	122.6	3.90								
	28 (Tremie)	2307	1301	2293	22.2	4.50	4.52	36.29	33.72													
		2304	1291	2274	22.1	4.52		34.01														
		2306.5	1291.5	2272	22.1	4.52		30.86														
	56	2298.5	1292.5	2285	21.4	4.67	4.69	54.16	54.10								11542	6499	2289	4165	39.7	39.7
		2357.5	1333	2301	21.3	4.69		54.15									11571	6509	2286	4170	39.7	
		2319.5	1304	2284	21.3	4.69		54														
	91	2305	1303	2300	21	4.76	4.78	58.1	59.24	3.601	2.032	2295	141	4.49	4.54	844	11541	6512	2295	4225	41.0	41.0
		2295	1296	2297	20.8	4.81		58.25		3.557	1.994	2276	144.8	4.61			11569.5	6517	2290	4235	41.1	
		2325	1325	2325	20.9	4.78		61.38		3.567	2.001	2278	142.5	4.54								
	91 (Tremie)	2337	1321	2300	21.1	4.74	4.75	40.48	41.97													
		2318.5	1308	2294	21	4.76		43.88														
		2319	1307	2292	21.1	4.74		41.54														
31	3	2392.5	1313.5	2217	23.8	4.20	4.21	18.64	18.51								11475.5	6427.5	2273	3570	29.0	29.0
TB		2320.5	1301.5	2277	23.8	4.20		18.26									11435	6399	2271	3580	29.1	
40% GGBS		2289.5	1286	2282	23.7	4.22		18.63														
	7	2317	1299	2276	23.0	4.35	4.35	30.09	29.13							2062	11491.5	6449	2279	3805	33.0	33.0

Appendix 6 Tabulated Results – Hardened Concrete Properties

		2313	1300.5	2284	23.0	4.35		28.06									11456	6430	2279	3808	33.1	
		2290	1281.5	2271	23.0	4.35		29.24														
	28	2277	1273	2268	22.3	4.48	4.50	48.04	46.24	3.5545	1.996	2281	142.9	4.55	4.37	1005	11504	6459	2280	4082	38.0	38.0
		2250	1260	2273	22.2	4.50		45.41		3.5585	1.997	2279	140.3	4.47			11471.5	6432.5	2277	4082	37.9	
		2297.5	1293.5	2288	22.2	4.50		45.27		3.596	2.018	2279	128.5	4.09								
	28 (Tremie)	2280	1275	2269	22	4.55	4.55	36.11	36.46													
		2332.5	1320.5	2305	22	4.55		35.38														
		2392	1360	2318	22	4.55		37.89														
	56	2339	1322	2300	21.8	4.59	4.57	50.68	50.54								11506	6466	2283	4136	39.1	39.2
		2299	1296	2292	21.9	4.57		50.9									11473	6434	2277	4156	39.3	
		2286	1289	2293	21.9	4.57		50.05														
	91	2314	1305	2293	21.7	4.61	4.62	52.51	53.90	3.561	2	2281	155.7	4.96	4.97	485	11512	6469	2283	4191	40.1	40.1
		2334	1312	2284	21.6	4.63		53.23		3.59	2.012	2275	154.4	4.91			11482	6443	2279	4197	40.1	
		2325	1309	2288	21.6	4.63		55.95		3.577	2.002	2271	157.9	5.03								
	91 (Tremie)	2315	1300	2281	21.7	4.61	4.59	40.62	41.31													
		2300	1303	2307	21.8	4.59		40.78														
		2312	1297	2278	21.8	4.59		42.54														
32	3	2270	1264	2256	23	4.35	4.35	20.4	20.32								11375	6352	2265	3653	30.2	30.0
TB		2283.5	1276.5	2268	23	4.35		20.52									11441.5	6390.5	2265	3630	29.8	
20% FA		2272	1267	2261	23	4.35		20.04														
	7	2275.5	1271.5	2266	22.6	4.42	4.42	25.17	25.21							4866	11395	6368	2267	3780	32.4	32.3
		2307	1293	2275	22.6	4.42		25.34									11451.5	6405.5	2269	3763	32.1	
		2317	1297	2272	22.6	4.42		25.12														
	28	2313	1300	2283	22.1	4.52	4.54	35.81	32.44	3.576	2	2269	83.8	2.67	2.93	1290	11406	6386	2272	3955	35.5	35.5
		2347.5	1330.5	2308	22	4.55		25.28		3.583	2.01	2278	107.2	3.41			11466.5	6423.5	2274	3945	35.4	
		2280	1278	2275	22	4.55		36.24		3.616	2.029	2279	85	2.71								

Appendix 6 Tabulated Results – Hardened Concrete Properties

	28 (Tremie)	2312	1306	2298	21.8	4.59	4.58	29.68	29.86													
		2298.5	1293.5	2287	21.9	4.57		27.77														
		2299	1295	2290	21.8	4.59		32.13														
	56	2298	1287	2273	21.9	4.57	4.59	40.09	41.02								11410	6389	2272	4033	37.0	36.8
		2286	1281	2275	21.8	4.59		41.5									11468	6424	2274	4018	36.7	
		2336	1314	2286	21.7	4.61		41.47														
	91	2349	1326	2296	21.4	4.67	4.66	45.38	45.48	3.584	2.011	2278	121.6	3.87	3.92	908	11414	6395	2274	4120	38.6	38.5
		2348	1315	2273	21.5	4.65		46.94		3.602	2.014	2268	128.1	4.08			11478	6434	2276	4106	38.4	
		2335	1310	2278	21.5	4.65		44.13		3.577	2.006	2277	119.6	3.81								
	91 (Tremie)	2300	1298	2295	21.5	4.65	4.64	37.88	39.47													
		2282	1288	2296	21.6	4.63		39.26														
		2287	1283	2278	21.6	4.63		41.28														

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

Table A7-1 Sorptivity raw data for SCC

SCC – C (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	4.41	0.441	4.55	0.455	4.61	0.461	0.45
0.6	5.59	0.559	5.82	0.582	6.21	0.621	0.59
0.8	6.5	0.65	6.74	0.674	7.4	0.74	0.69
0.9	7.12	0.712	7.45	0.745	8.23	0.823	0.76
1.0	7.77	0.777	7.92	0.792	8.86	0.886	0.82
1.1	8.25	0.825	8.5	0.85	9.49	0.949	0.87
1.2	8.79	0.879	9.02	0.902	10	1	0.93
1.2	8.96	0.896	9.24	0.924	10.25	1.025	0.95
1.5	10.37	1.037	10.43	1.043	11.36	1.136	1.07
1.5	10.6	1.06	10.65	1.065	11.59	1.159	1.09
1.6	10.95	1.095	10.9	1.09	11.79	1.179	1.12
1.7	11.53	1.153	11.35	1.135	12.2	1.22	1.17
1.8	12.15	1.215	11.92	1.192	12.58	1.258	1.22
1.9	12.4	1.24	12.07	1.207	12.75	1.275	1.24
1.9	12.62	1.262	12.25	1.225	12.94	1.294	1.26
2.0	12.86	1.286	12.51	1.251	13.02	1.302	1.28
5.0	24.32	2.432	20.12	2.012	19.89	1.989	2.14
7.0	29.38	2.938	23.57	2.357	23.45	2.345	2.55
9.0	33.24	3.324	26.75	2.675	26.75	2.675	2.89
10.2	34.79	3.479	28.33	2.833	28.05	2.805	3.04
10.9	35.85	3.585	29.04	2.904	29.06	2.906	3.13
12.0	36.57	3.657	29.92	2.992	30.01	3.001	3.22
13.0	37.73	3.773	31.27	3.127	31.06	3.106	3.34
13.8	38.59	3.859	31.98	3.198	31.96	3.196	3.42
14.7	39.51	3.951	33.19	3.319	32.96	3.296	3.52
15.6	40.2	4.02	33.86	3.386	33.79	3.379	3.59
16.4	40.72	4.072	34.52	3.452	34.39	3.439	3.65
17.1	41.22	4.122	35.17	3.517	35.08	3.508	3.72
17.7	41.7	4.17	35.65	3.565	35.59	3.559	3.76
18.4	41.98	4.198	35.96	3.596	35.99	3.599	3.80
19.0	42.65	4.265	36.99	3.699	36.79	3.679	3.88
19.6	43.13	4.313	37.48	3.748	37.28	3.728	3.93
20.3	43.66	4.366	38.06	3.806	37.92	3.792	3.99
20.9	44.01	4.401	38.65	3.865	38.5	3.85	4.04
21.4	44.44	4.444	39.07	3.907	38.9	3.89	4.08
22.0	44.89	4.489	39.47	3.947	39.36	3.936	4.12
22.5	45.29	4.529	40.03	4.003	39.73	3.973	4.17

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	5.13	0.513	4.79	0.479	5.33	0.533	0.51
0.6	6.09	0.609	6.24	0.624	6.84	0.684	0.64
0.8	6.82	0.682	7.3	0.73	7.75	0.775	0.73
0.9	7.49	0.749	8.24	0.824	8.55	0.855	0.81
1.0	8.02	0.802	8.95	0.895	9.17	0.917	0.87
1.2	9.09	0.909	10.43	1.043	10.3	1.03	0.99
1.4	10.26	1.026	11.65	1.165	10.84	1.084	1.09
1.6	11.09	1.109	12.88	1.288	12.52	1.252	1.22
1.8	12.22	1.222	13.77	1.377	13.24	1.324	1.31
2.0	12.97	1.297	14.8	1.48	14.13	1.413	1.40
4.7	20.05	2.005	22.06	2.206	20.24	2.024	2.08
6.2	22.56	2.256	24.57	2.457	22.62	2.262	2.33
7.9	24.82	2.482	26.35	2.635	24.62	2.462	2.53
9.3	26.59	2.659	27.98	2.798	26.42	2.642	2.70
10.5	27.64	2.764	29.08	2.908	27.6	2.76	2.81
11.6	28.63	2.863	30.18	3.018	28.93	2.893	2.92
12.8	29.53	2.953	31.16	3.116	29.78	2.978	3.02
13.7	29.92	2.992	31.53	3.153	30.56	3.056	3.07
14.5	30.62	3.062	32.51	3.251	31.26	3.126	3.15
15.2	31.21	3.121	33.24	3.324	31.94	3.194	3.21
16.0	31.63	3.163	33.55	3.355	32.48	3.248	3.26
16.7	32.19	3.219	33.87	3.387	33	3.3	3.30
17.4	33.11	3.311	34.49	3.449	33.44	3.344	3.37
18.1	33.44	3.344	34.94	3.494	34.08	3.408	3.42
18.8	34.25	3.425	35.34	3.534	34.57	3.457	3.47
19.4	34.66	3.466	35.75	3.575	34.94	3.494	3.51
20.1	35.13	3.513	36.24	3.624	35.41	3.541	3.56
20.6	35.5	3.55	36.75	3.675	35.72	3.572	3.60
21.2	36.33	3.633	37.23	3.723	36	3.6	3.65
21.7	36.52	3.652	37.46	3.746	36.2	3.62	3.67
22.9	37.04	3.704	38.05	3.805	36.86	3.686	3.73

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G40 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	4.29	0.429	4.99	0.499	3.97	0.397	0.44
0.6	5.64	0.564	6.28	0.628	5.09	0.509	0.57
0.8	6.42	0.642	7.17	0.717	5.74	0.574	0.64
0.9	7.24	0.724	8.02	0.802	6.48	0.648	0.72
1.0	7.99	0.799	8.83	0.883	7.17	0.717	0.80
1.3	9.44	0.944	10.04	1.004	8.36	0.836	0.93
1.3	9.73	0.973	10.32	1.032	8.67	0.867	0.96
1.4	10.15	1.015	10.71	1.071	8.94	0.894	0.99
1.5	10.5	1.05	11.12	1.112	9.32	0.932	1.03
1.7	11.44	1.144	12	1.2	10.17	1.017	1.12
1.8	11.86	1.186	12.38	1.238	10.45	1.045	1.16
1.9	12.17	1.217	12.92	1.292	10.84	1.084	1.20
1.9	12.33	1.233	13.05	1.305	10.98	1.098	1.21
2.0	12.47	1.247	13.19	1.319	11.16	1.116	1.23
4.8	19.5	1.95	19.54	1.954	17.53	1.753	1.89
7.0	23.05	2.305	21.85	2.185	19.98	1.998	2.16
8.7	24.76	2.476	23.39	2.339	21.39	2.139	2.32
10.1	25.1	2.51	23.96	2.396	22.25	2.225	2.38
11.1	26.14	2.614	24.72	2.472	23.07	2.307	2.46
12.0	26.86	2.686	25.82	2.582	23.62	2.362	2.54
13.0	27.12	2.712	26.25	2.625	24.14	2.414	2.58
13.9	27.86	2.786	26.98	2.698	24.9	2.49	2.66
14.7	28.3	2.83	27.69	2.769	25.29	2.529	2.71
15.6	28.82	2.882	28.22	2.822	25.87	2.587	2.76
16.3	29.18	2.918	28.85	2.885	26.36	2.636	2.81
17.0	29.71	2.971	29.34	2.934	26.77	2.677	2.86
17.8	30.48	3.048	29.9	2.99	27.31	2.731	2.92
18.4	30.68	3.068	30.19	3.019	27.6	2.76	2.95
19.1	31.04	3.104	30.53	3.053	28	2.8	2.99
19.6	31.35	3.135	30.82	3.082	28.28	2.828	3.01
20.9	32.13	3.213	31.62	3.162	28.95	2.895	3.09
21.4	32.75	3.275	32.19	3.219	29.44	2.944	3.15
22.0	33.31	3.331	32.44	3.244	29.71	2.971	3.18
22.5	33.82	3.382	33.04	3.304	30.23	3.023	3.24

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G60 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	4.03	0.403	4.57	0.457	4.05	0.405	0.42
0.6	5.47	0.547	6.02	0.602	5.37	0.537	0.56
0.8	6.58	0.658	7.32	0.732	6.34	0.634	0.67
0.9	7.24	0.724	7.97	0.797	6.95	0.695	0.74
1.0	7.9	0.79	8.81	0.881	7.62	0.762	0.81
1.1	8.4	0.84	9.34	0.934	8.1	0.81	0.86
1.2	8.81	0.881	9.98	0.998	8.51	0.851	0.91
1.3	9.39	0.939	10.47	1.047	9.02	0.902	0.96
1.3	9.72	0.972	10.92	1.092	9.43	0.943	1.00
1.4	10.14	1.014	11.38	1.138	9.77	0.977	1.04
1.5	10.49	1.049	11.78	1.178	10.14	1.014	1.08
1.5	10.88	1.088	12.19	1.219	10.37	1.037	1.11
1.7	11.55	1.155	12.89	1.289	11.13	1.113	1.19
1.7	11.93	1.193	13.28	1.328	11.44	1.144	1.22
1.8	12.26	1.226	13.6	1.36	11.7	1.17	1.25
1.8	12.5	1.25	13.85	1.385	11.98	1.198	1.28
1.9	12.92	1.292	14.11	1.411	12.19	1.219	1.31
5.1	26.26	2.626	26.54	2.654	22.88	2.288	2.52
6.9	30.51	3.051	29.39	2.939	25.32	2.532	2.84
8.3	36.04	3.604	31.28	3.128	26.64	2.664	3.13
9.7	37.65	3.765	32.8	3.28	27.62	2.762	3.27
10.8	38.9	3.89	33.89	3.389	28.63	2.863	3.38
11.9	39.77	3.977	34.46	3.446	29.2	2.92	3.45
12.9	40.64	4.064	35.29	3.529	29.97	2.997	3.53
13.8	41.13	4.113	36.02	3.602	30.63	3.063	3.59
14.6	41.73	4.173	36.54	3.654	31.15	3.115	3.65
15.5	42.64	4.264	37.34	3.734	31.76	3.176	3.72
16.2	42.84	4.284	37.69	3.769	32.14	3.214	3.76
17.0	43.49	4.349	38.26	3.826	32.71	3.271	3.82
17.6	43.63	4.363	38.56	3.856	32.9	3.29	3.84
19.0	44.39	4.439	39.49	3.949	33.82	3.382	3.92
19.6	45.09	4.509	40.11	4.011	34.33	3.433	3.98
20.2	45.41	4.541	40.58	4.058	34.62	3.462	4.02
20.7	45.82	4.582	41.04	4.104	35.34	3.534	4.07
21.4	46.27	4.627	42.01	4.201	35.95	3.595	4.14
21.8	46.94	4.694	42.48	4.248	36.32	3.632	4.19
23.0	47.16	4.716	43.2	4.32	37.22	3.722	4.25

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G80 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	2.65	0.265	3.11	0.311	4	0.4	0.33
0.6	4.16	0.416	4.55	0.455	6.22	0.622	0.50
0.8	5.04	0.504	5.39	0.539	7.48	0.748	0.60
0.9	5.91	0.591	6.16	0.616	9.03	0.903	0.70
1.0	6.51	0.651	6.7	0.67	9.98	0.998	0.77
1.1	7.12	0.712	7.26	0.726	10.92	1.092	0.84
1.3	8.26	0.826	8.28	0.828	12.61	1.261	0.97
1.4	8.96	0.896	8.9	0.89	13.84	1.384	1.06
1.5	9.67	0.967	9.54	0.954	15.02	1.502	1.14
1.6	10	1	9.8	0.98	15.62	1.562	1.18
1.7	10.27	1.027	10.03	1.003	16	1.6	1.21
1.7	10.55	1.055	10.31	1.031	16.52	1.652	1.25
1.8	10.83	1.083	10.5	1.05	16.93	1.693	1.28
1.8	11.21	1.121	10.91	1.091	18.86	1.886	1.37
1.9	11.48	1.148	11.11	1.111	19.28	1.928	1.40
1.9	11.77	1.177	11.38	1.138	19.75	1.975	1.43
2.0	12.02	1.202	11.5	1.15	20.25	2.025	1.46
4.9	23.84	2.384	22.57	2.257	35.64	3.564	2.74
6.9	28.91	2.891	28.02	2.802	43.17	4.317	3.34
8.5	31.75	3.175	31.41	3.141	47.91	4.791	3.70
9.9	33.34	3.334	33.55	3.355	51.04	5.104	3.93
11.0	34.7	3.47	35.04	3.504	53.11	5.311	4.10
12.1	35.78	3.578	36.33	3.633	54.84	5.484	4.23
13.0	36.77	3.677	37.5	3.75	56.28	5.628	4.35
13.9	37.32	3.732	38.45	3.845	57.32	5.732	4.44
14.7	37.99	3.799	39.05	3.905	57.92	5.792	4.50
16.4	39.14	3.914	40.87	4.087	59.93	5.993	4.66
17.0	39.73	3.973	41.45	4.145	60.85	6.085	4.73
17.7	40.15	4.015	41.9	4.19	61.61	6.161	4.79
18.3	40.79	4.079	42.58	4.258	62.5	6.25	4.86
19.0	41.39	4.139	43.15	4.315	63.24	6.324	4.93
19.6	41.85	4.185	43.6	4.36	63.96	6.396	4.98
20.8	42.51	4.251	44.74	4.474	65.08	6.508	5.08
21.4	42.88	4.288	45.1	4.51	65.51	6.551	5.12
21.9	43.26	4.326	45.46	4.546	65.87	6.587	5.15
22.4	43.98	4.398	45.94	4.594	66.34	6.634	5.21

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	3.94	0.394	4.63	0.463	3.99	0.399	0.42
0.6	5.11	0.511	5.92	0.592	5.41	0.541	0.55
0.8	6.13	0.613	6.89	0.689	6.29	0.629	0.64
0.9	6.84	0.684	7.6	0.76	6.74	0.674	0.71
1.0	7.29	0.729	8.04	0.804	7.1	0.71	0.75
1.1	7.76	0.776	8.57	0.857	7.53	0.753	0.80
1.2	8.24	0.824	9.06	0.906	7.89	0.789	0.84
1.3	8.53	0.853	9.3	0.93	8.11	0.811	0.86
1.4	9.08	0.908	9.76	0.976	8.58	0.858	0.91
1.5	9.24	0.924	9.98	0.998	8.71	0.871	0.93
1.6	9.8	0.98	10.51	1.051	9.09	0.909	0.98
1.7	10.09	1.009	10.72	1.072	9.31	0.931	1.00
1.8	10.18	1.018	10.81	1.081	9.41	0.941	1.01
1.8	10.27	1.027	10.87	1.087	9.51	0.951	1.02
1.9	10.43	1.043	10.98	1.098	9.61	0.961	1.03
1.9	10.66	1.066	11.08	1.108	9.73	0.973	1.05
4.9	14.7	1.47	14.84	1.484	13.86	1.386	1.45
6.9	17.36	1.736	17.23	1.723	16.4	1.64	1.70
8.5	19.13	1.913	19.02	1.902	18.23	1.823	1.88
9.8	20.55	2.055	20.53	2.053	19.57	1.957	2.02
11.0	21.96	2.196	21.8	2.18	20.82	2.082	2.15
11.9	22.69	2.269	22.63	2.263	21.55	2.155	2.23
14.0	24.28	2.428	24.53	2.453	23.45	2.345	2.41
14.7	25.22	2.522	25.38	2.538	24.23	2.423	2.49
15.5	25.97	2.597	26.11	2.611	24.87	2.487	2.57
16.2	26.52	2.652	26.85	2.685	25.59	2.559	2.63
17.0	27.62	2.762	27.58	2.758	26.28	2.628	2.72
17.6	28	2.8	28.32	2.832	26.92	2.692	2.77
19.0	29.43	2.943	29.69	2.969	28.25	2.825	2.91
19.6	29.66	2.966	30.26	3.026	28.69	2.869	2.95
20.2	30.3	3.03	30.59	3.059	29.08	2.908	3.00
20.7	30.78	3.078	31.1	3.11	29.56	2.956	3.05
21.3	31.92	3.192	31.71	3.171	29.89	2.989	3.12
21.8	32.33	3.233	32.09	3.209	30.44	3.044	3.16
23.5	33.77	3.377	33.66	3.366	32.04	3.204	3.32

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F40 (7 days)

Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	5.89	0.589	4.91	0.491	5.76	0.576	0.55
0.6	7.9	0.79	6.87	0.687	7.62	0.762	0.75
0.8	9.26	0.926	8.21	0.821	9.05	0.905	0.88
0.9	10.64	1.064	9.36	0.936	9.88	0.988	1.00
1.0	11.72	1.172	10.41	1.041	11.24	1.124	1.11
1.2	13.17	1.317	11.86	1.186	13.07	1.307	1.27
1.4	14.87	1.487	14.02	1.402	14.64	1.464	1.45
1.5	16.13	1.613	15.07	1.507	15.43	1.543	1.55
1.6	16.65	1.665	15.41	1.541	15.76	1.576	1.59
1.7	17.15	1.715	15.95	1.595	16.26	1.626	1.65
1.7	17.84	1.784	16.48	1.648	16.86	1.686	1.71
1.9	19.26	1.926	17.69	1.769	18.36	1.836	1.84
1.9	19.51	1.951	18.14	1.814	18.62	1.862	1.88
2.0	20.04	2.004	18.6	1.86	19.03	1.903	1.92
4.9	39.5	3.95	36.73	3.673	38.07	3.807	3.81
6.9	48.89	4.889	44.94	4.494	47.08	4.708	4.70
8.7	54.55	5.455	49.38	4.938	51.87	5.187	5.19
9.9	57.62	5.762	51.81	5.181	54.83	5.483	5.48
11.2	59.75	5.975	53.84	5.384	57.14	5.714	5.69
11.9	60.84	6.084	54.85	5.485	58.36	5.836	5.80
13.2	62.08	6.208	56.25	5.625	60.11	6.011	5.95
13.9	63.1	6.31	56.87	5.687	61.22	6.122	6.04
14.7	64.18	6.418	57.9	5.79	62.26	6.226	6.14
15.7	64.85	6.485	58.52	5.852	62.94	6.294	6.21
16.4	65.44	6.544	59.03	5.903	63.33	6.333	6.26
17.1	65.78	6.578	59.61	5.961	64.12	6.412	6.32
17.9	66.2	6.62	60.14	6.014	64.92	6.492	6.38
18.4	66.59	6.659	60.61	6.061	65.31	6.531	6.42
19.0	66.84	6.684	60.79	6.079	65.6	6.56	6.44
19.7	67.61	6.761	61.48	6.148	66.63	6.663	6.52
20.4	68.46	6.846	61.89	6.189	67.13	6.713	6.58
20.9	68.77	6.877	62.17	6.217	67.25	6.725	6.61
21.4	69.03	6.903	62.53	6.253	67.85	6.785	6.65
22.0	69.37	6.937	62.75	6.275	68.11	6.811	6.67
22.5	69.6	6.96	63.14	6.314	68.57	6.857	6.71

SCC – F60 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	9.16	0.916	8.41	0.841	9.11	0.911	0.89
0.6	11.94	1.194	10.93	1.093	12.16	1.216	1.17
0.8	14.35	1.435	13.37	1.337	14.52	1.452	1.41
0.9	16.06	1.606	15	1.5	16.37	1.637	1.58
1.0	18.06	1.806	16.92	1.692	18.37	1.837	1.78
1.1	19.76	1.976	18.78	1.878	20.31	2.031	1.96
1.3	22.25	2.225	21.38	2.138	22.77	2.277	2.21
1.5	24.98	2.498	23.75	2.375	25.74	2.574	2.48
1.6	25.62	2.562	24.49	2.449	26.25	2.625	2.55
1.7	26.41	2.641	25.18	2.518	26.99	2.699	2.62
1.7	27.45	2.745	27.09	2.709	28.24	2.824	2.76
1.8	28.67	2.867	27.88	2.788	30.24	3.024	2.89
1.9	29.46	2.946	28.61	2.861	30.93	3.093	2.97
1.9	29.81	2.981	29.01	2.901	31.28	3.128	3.00
2.0	30.5	3.05	29.62	2.962	31.94	3.194	3.07
4.8	53.78	5.378	51.04	5.104	54.3	5.43	5.30
7.2	65.26	6.526	61.55	6.155	65.21	6.521	6.40
8.7	69.54	6.954	65.91	6.591	69.74	6.974	6.84
10.0	72.53	7.253	68.56	6.856	72.39	7.239	7.12
11.3	75	7.5	70.7	7.07	74.7	7.47	7.35
12.1	76.25	7.625	71.88	7.188	75.89	7.589	7.47
12.9	77.24	7.724	72.81	7.281	76.72	7.672	7.56
13.9	78.55	7.855	74.5	7.45	78.24	7.824	7.71
15.0	80.32	8.032	76.19	7.619	79.44	7.944	7.87
15.6	80.82	8.082	76.81	7.681	80.08	8.008	7.92
16.2	81.61	8.161	77.76	7.776	80.88	8.088	8.01
17.0	82.2	8.22	78.51	7.851	81.64	8.164	8.08
17.7	82.71	8.271	79.6	7.96	82.75	8.275	8.17
18.4	83.59	8.359	80.25	8.025	84.01	8.401	8.26
19.9	85.17	8.517	82.43	8.243	86.8	8.68	8.48
20.4	85.33	8.533	83.02	8.302	87.91	8.791	8.54
21.0	85.97	8.597	83.93	8.393	89.17	8.917	8.64
21.5	86.59	8.659	84.94	8.494	89.76	8.976	8.71
22.0	87.01	8.701	85.44	8.544	90.45	9.045	8.76
22.5	87.36	8.736	85.89	8.589	92.16	9.216	8.85

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F80 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	13.05	1.305	11.94	1.194	16.1	1.61	1.37
0.6	17.1	1.71	15.1	1.51	20.51	2.051	1.76
0.8	20.37	2.037	17.86	1.786	24.2	2.42	2.08
0.9	23.12	2.312	20.16	2.016	27	2.7	2.34
1.0	25.9	2.59	22.52	2.252	30.14	3.014	2.62
1.1	28.69	2.869	24.74	2.474	33.14	3.314	2.89
1.3	32.685	3.2685	28.115	2.8115	37.475	3.7475	3.28
1.5	36.68	3.668	31.49	3.149	41.81	4.181	3.67
1.6	37.54	3.754	32.27	3.227	42.95	4.295	3.76
1.7	38.69	3.869	33.35	3.335	44.15	4.415	3.87
1.7	40.33	4.033	34.7	3.47	46.06	4.606	4.04
1.8	42.25	4.225	36.32	3.632	48.12	4.812	4.22
1.9	43.39	4.339	37.28	3.728	49.23	4.923	4.33
1.9	43.84	4.384	37.64	3.764	49.88	4.988	4.38
2.0	45.18	4.518	38.49	3.849	51.47	5.147	4.50
4.8	87.35	8.735	75.6	7.56	99.92	9.992	8.76
7.2	114.47	11.447	100.34	10.034	133.18	13.318	11.60
8.7	127.99	12.799	112.66	11.266	149.13	14.913	12.99
10.0	137.15	13.715	121.62	12.162	160.42	16.042	13.97
11.3	145.46	14.546	129.59	12.959	169.04	16.904	14.80
12.1	149.94	14.994	134.22	13.422	172.58	17.258	15.22
12.9	153.63	15.363	137.86	13.786	174.5	17.45	15.53
13.9	158.4	15.84	141.97	14.197	176.56	17.656	15.90
15.0	162.95	16.295	145.95	14.595	177.62	17.762	16.22
15.6	165.15	16.515	147.6	14.76	178.14	17.814	16.36
16.2	167.21	16.721	148.53	14.853	178.5	17.85	16.47
17.0	169.52	16.952	149.28	14.928	178.61	17.861	16.58
17.7	171	17.1	150.12	15.012	178.99	17.899	16.67
18.4	172.73	17.273	151.54	15.154	180.32	18.032	16.82
19.9	175.4	17.54	152.66	15.266	180.95	18.095	16.97
20.4	175.97	17.597	152.66	15.266	180.95	18.095	16.99
21.0	176.37	17.637	152.66	15.266	180.95	18.095	17.00
21.5	176.53	17.653	152.9	15.29	181.1	18.11	17.02
22.0	176.99	17.699	153.12	15.312	181.35	18.135	17.05
22.5	177.19	17.719	153.12	15.312	181.35	18.135	17.06

SCC – L10 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	5.12	0.512	6.19	0.619	6.01	0.601	0.58
0.6	7.91	0.791	9.37	0.937	8.17	0.817	0.85
0.8	10.81	1.081	12.56	1.256	10.66	1.066	1.13
0.9	12.01	1.201	13.5	1.35	11.65	1.165	1.24
1.0	13.07	1.307	14.69	1.469	12.58	1.258	1.34
1.1	14.21	1.421	16.01	1.601	13.81	1.381	1.47
1.4	17.25	1.725	19.95	1.995	17.13	1.713	1.81
1.5	17.95	1.795	20.72	2.072	17.79	1.779	1.88
1.5	18.71	1.871	21.9	2.19	18.53	1.853	1.97
1.6	19.46	1.946	22.65	2.265	19.02	1.902	2.04
1.7	20.21	2.021	23.38	2.338	19.76	1.976	2.11
1.7	20.73	2.073	24.17	2.417	20.43	2.043	2.18
1.8	21.78	2.178	25.68	2.568	21.51	2.151	2.30
1.9	22.37	2.237	26.25	2.625	21.94	2.194	2.35
4.9	41.63	4.163	50.1	5.01	42.77	4.277	4.48
6.9	49.86	4.986	62.17	6.217	52.03	5.203	5.47
8.5	53.83	5.383	69.41	6.941	58.71	5.871	6.06
10.0	56.45	5.645	74.4	7.44	61.99	6.199	6.43
11.1	58.47	5.847	77.56	7.756	64.57	6.457	6.69
12.0	59.45	5.945	79.2	7.92	65.57	6.557	6.81
13.0	60.46	6.046	80.98	8.098	66.76	6.676	6.94
13.9	60.90	6.09	82.29	8.229	67.67	6.767	7.03
15.4	62.15	6.215	84.04	8.404	69.23	6.923	7.18
17.1	63.95	6.395	85.89	8.589	70.92	7.092	7.36
18.3	64.86	6.486	87.03	8.703	72.27	7.227	7.47
19.0	65.36	6.536	87.73	8.773	72.58	7.258	7.52
19.6	67.02	6.702	88.8	8.88	73.55	7.355	7.65
20.0	67.15	6.715	89.64	8.964	73.85	7.385	7.69
20.6	67.65	6.765	90.32	9.032	74.2	7.42	7.74

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – L20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	6.31	0.631	8.13	0.813	7.16	0.716	0.72
0.6	8.31	0.831	10.93	1.093	9.48	0.948	0.96
0.8	10.66	1.066	14.5	1.45	12.77	1.277	1.26
0.9	11.59	1.159	16.04	1.604	14.08	1.408	1.39
1.0	12.52	1.252	17.4	1.74	15.46	1.546	1.51
1.1	13.83	1.383	19.32	1.932	17.13	1.713	1.68
1.4	17.40	1.74	24.32	2.432	21.86	2.186	2.12
1.5	18.23	1.823	25.81	2.581	22.77	2.277	2.23
1.5	18.85	1.885	26.67	2.667	23.55	2.355	2.30
1.6	19.52	1.952	27.85	2.785	24.32	2.432	2.39
1.7	20.09	2.009	28.72	2.872	25.07	2.507	2.46
1.7	21.01	2.101	29.73	2.973	26.01	2.601	2.56
1.8	22.23	2.223	31.69	3.169	27.48	2.748	2.71
1.9	22.73	2.273	32.53	3.253	28.36	2.836	2.79
4.9	46.67	4.667	62.03	6.203	55.34	5.534	5.47
6.9	59.45	5.945	77.4	7.74	69.11	6.911	6.87
8.5	66.85	6.685	86	8.6	77.78	7.778	7.69
10.0	72.24	7.224	91.85	9.185	83.06	8.306	8.24
11.1	75.99	7.599	96.35	9.635	86.53	8.653	8.63
12.0	78.66	7.866	97.84	9.784	88.74	8.874	8.84
13.0	81.01	8.101	99.45	9.945	90.35	9.035	9.03
13.9	82.76	8.276	100.49	10.049	91.94	9.194	9.17
15.4	84.86	8.486	101.91	10.191	94.97	9.497	9.39
17.1	87.05	8.705	103.12	10.312	95.75	9.575	9.53
18.3	88.53	8.853	103.93	10.393	96.88	9.688	9.64
19.0	88.88	8.888	104.16	10.416	97.33	9.733	9.68
19.6	90.07	9.007	104.85	10.485	98.23	9.823	9.77
20.0	90.54	9.054	105.18	10.518	98.98	9.898	9.82
20.6	90.82	9.082	105.38	10.538	99.08	9.908	9.84

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – L30 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	8.19	0.819	7.97	0.797	8.5	0.85	0.82
0.6	13.07	1.307	12.6	1.26	13.47	1.347	1.30
0.8	15.94	1.594	15.74	1.574	16.65	1.665	1.61
0.9	18.22	1.822	18.11	1.811	19.24	1.924	1.85
1.5	25.07	2.507	25.32	2.532	27.33	2.733	2.59
1.7	26.75	2.675	27.21	2.721	29.44	2.944	2.78
1.8	27.59	2.759	28.3	2.83	31.39	3.139	2.91
1.9	28.79	2.879	29.36	2.936	32.5	3.25	3.02
5.1	54.37	5.437	56.43	5.643	61.77	6.177	5.75
7.1	67	6.7	70.49	7.049	74.95	7.495	7.08
8.7	75.33	7.533	80.39	8.039	83.87	8.387	7.99
12.1	84.43	8.443	89.83	8.983	92.44	9.244	8.89
13.1	86.43	8.643	91.98	9.198	95.79	9.579	9.14
14.1	88.52	8.852	94.59	9.459	98.5	9.85	9.39
14.9	89.39	8.939	95.46	9.546	99.11	9.911	9.47
15.7	90.72	9.072	96.91	9.691	100.36	10.036	9.60
18.7	93.08	9.308	101.06	10.106	104.73	10.473	9.96
19.3	93.95	9.395	101.83	10.183	105.45	10.545	10.04
19.9	94.86	9.486	103.01	10.301	106.12	10.612	10.13
20.5	95.56	9.556	103.64	10.364	106.81	10.681	10.20
21.1	96.51	9.651	105.1	10.51	107.77	10.777	10.31
21.6	96.99	9.699	105.18	10.518	108.27	10.827	10.35
22.2	97.25	9.725	105.39	10.539	108.72	10.872	10.38
22.7	97.53	9.753	105.47	10.547	108.9	10.89	10.40

SCC – TB – G20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	8.49	0.849	10.7	1.07	11.05	1.105	1.01
0.6	10.62	1.062	13.45	1.345	14.13	1.413	1.27
0.8	12.51	1.251	15.42	1.542	16.05	1.605	1.47
0.9	13.59	1.359	17.04	1.704	19.16	1.916	1.66
1.1	14.94	1.494	18.39	1.839	20.51	2.051	1.79
1.4	16.39	1.639	19.84	1.984	21.96	2.196	1.94
1.5	17.81	1.781	22.62	2.262	24.45	2.445	2.16
1.7	18.66	1.866	24	2.4	25.5	2.55	2.27
1.8	19.3	1.93	24.92	2.492	26.58	2.658	2.36
1.9	19.93	1.993	25.98	2.598	27.32	2.732	2.44
5.1	34.55	3.455	47.75	4.775	46.54	4.654	4.29
7.1	41.3	4.13	57.66	5.766	54.26	5.426	5.11
8.7	44.19	4.419	61.86	6.186	58.27	5.827	5.48
12.1	51.11	5.111	71.59	7.159	66.97	6.697	6.32
13.1	54.15	5.415	76.09	7.609	71.71	7.171	6.73
14.1	55.15	5.515	78.13	7.813	72.98	7.298	6.88
14.9	55.36	5.536	79.71	7.971	74.91	7.491	7.00
15.7	56.56	5.656	80.35	8.035	75.59	7.559	7.08
18.7	59.06	5.906	83.98	8.398	78.99	7.899	7.40
19.3	59.96	5.996	84.77	8.477	79.6	7.96	7.48
19.9	60.8	6.08	85.7	8.57	80.23	8.023	7.56
20.5	61.94	6.194	86.11	8.611	80.77	8.077	7.63
21.1	62.23	6.223	86.64	8.664	81.23	8.123	7.67
21.6	62.76	6.276	87.44	8.744	81.69	8.169	7.73
22.2	63.4	6.34	87.45	8.745	82.02	8.202	7.76
22.7	63.66	6.366	88.15	8.815	82.41	8.241	7.81

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – G40 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	6.03	0.603	5.62	0.562	6.51	0.651	0.61
0.6	7.41	0.741	7.26	0.726	8.33	0.833	0.77
0.8	8.48	0.848	8.2	0.82	9.56	0.956	0.87
0.9	9.29	0.929	9.2	0.92	10.43	1.043	0.96
1.0	10.18	1.018	10.01	1.001	11.29	1.129	1.05
1.1	11.58	1.158	11.41	1.141	12.69	1.269	1.19
1.4	12.86	1.2855	12.685	1.2685	13.965	1.3965	1.32
1.6	14.34	1.434	13.82	1.382	15.84	1.584	1.47
1.7	14.99	1.499	14.43	1.443	16.5	1.65	1.53
1.8	15.39	1.539	14.82	1.482	16.95	1.695	1.57
1.9	16.15	1.615	15.32	1.532	17.75	1.775	1.64
2.0	16.65	1.665	15.99	1.599	18.41	1.841	1.70
5.5	35.54	3.554	33.28	3.328	34.92	3.492	3.46
7.2	43.08	4.308	40.31	4.031	39.86	3.986	4.11
8.8	47.85	4.785	44.97	4.497	42.53	4.253	4.51
10.1	50.72	5.072	47.72	4.772	43.75	4.375	4.74
11.2	52.66	5.266	49.95	4.995	45.16	4.516	4.93
12.0	53.86	5.386	51.21	5.121	46.1	4.61	5.04
13.2	55.22	5.522	52.84	5.284	47.01	4.701	5.17
14.1	56.51	5.651	54.29	5.429	47.95	4.795	5.29
14.8	56.53	5.653	54.37	5.437	48.95	4.895	5.33
15.7	57.88	5.788	54.45	5.445	49.88	4.988	5.41
16.4	58.76	5.876	57.61	5.761	51.05	5.105	5.58
17.1	59.11	5.911	57.77	5.777	51.44	5.144	5.61
17.7	59.59	5.959	58.49	5.849	52.09	5.209	5.67
18.4	60.03	6.003	58.94	5.894	52.53	5.253	5.72
19.1	60.75	6.075	59.69	5.969	53.27	5.327	5.79
19.6	60.86	6.086	59.98	5.998	53.55	5.355	5.81
20.3	61.16	6.116	60.47	6.047	54.08	5.408	5.86
20.9	61.46	6.146	60.77	6.077	54.38	5.438	5.89
21.4	61.76	6.176	61.07	6.107	54.68	5.468	5.92
22.0	62.06	6.206	61.37	6.137	54.98	5.498	5.95
22.5	62.36	6.236	61.67	6.167	55.28	5.528	5.98

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – G60 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	5.62	0.562	6.38	0.638	6.01	0.601	0.60
0.8	8.68	0.868	10.4	1.04	9.83	0.983	0.96
0.9	10.99	1.099	12.69	1.269	12.07	1.207	1.19
1.2	12.19	1.219	13.89	1.389	13.27	1.327	1.31
1.4	13.45	1.345	15.15	1.515	14.53	1.453	1.44
1.5	14.68	1.468	16.38	1.638	15.76	1.576	1.56
1.7	15.90	1.59	17.6	1.76	16.98	1.698	1.68
1.8	17.14	1.714	19.88	1.988	19.33	1.933	1.88
1.9	17.92	1.792	20.68	2.068	20	2	1.95
2.0	18.61	1.861	21.35	2.135	20.51	2.051	2.02
5.1	35.36	3.536	37.48	3.748	37.11	3.711	3.66
6.8	41.79	4.179	43.08	4.308	42.88	4.288	4.26
10.9	49.89	4.989	51.18	5.118	50.98	5.098	5.07
12.0	52.44	5.244	53.73	5.373	53.53	5.353	5.32
13.0	54.97	5.497	54.46	5.446	53.74	5.374	5.44
21.4	60.15	6.015	60.21	6.021	58.27	5.827	5.95
22.0	60.51	6.051	60.62	6.062	58.47	5.847	5.99
22.4	60.53	6.053	60.62	6.062	58.64	5.864	5.99

SCC – TB – G80 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m²)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m²)**	**Water intake (g)**	**Water intake/unit area (Kg/m²)**	**Water intake (g)**	**Water intake/unit area (Kg/m²)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	7.72	0.772	7.17	0.717	7.39	0.739	0.74
0.8	11.30	1.13	10.1	1.01	10.95	1.095	1.08
0.9	13.45	1.345	11.65	1.165	12.87	1.287	1.27
1.8	19.55	1.955	16.74	1.674	19.54	1.954	1.86
1.9	20.62	2.062	17.13	1.713	20.01	2.001	1.93
2.0	21.69	2.169	17.92	1.792	20.52	2.052	2.00
5.1	36.57	3.657	29.57	2.957	35.66	3.566	3.39
6.8	42.07	4.207	34.67	3.467	41.81	4.181	3.95
13.0	49.24	4.924	41.85	4.185	51.31	5.131	4.75
21.4	53.34	5.334	46.11	4.611	55.96	5.596	5.18
22.0	53.57	5.357	46.21	4.621	56.07	5.607	5.20
22.4	53.57	5.357	46.39	4.639	56.35	5.635	5.21

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – F20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	7.40	0.74	7.11	0.711	6.72	0.672	0.71
0.8	11.71	1.171	11.41	1.141	10.78	1.078	1.13
0.9	14.12	1.412	14.38	1.438	13.52	1.352	1.40
1.8	22.71	2.271	23.26	2.326	22.53	2.253	2.28
1.9	23.94	2.394	23.86	2.386	23.34	2.334	2.37
2.0	24.84	2.484	24.74	2.474	24.14	2.414	2.46
5.1	44.29	4.429	44.37	4.437	45.17	4.517	4.46
6.8	52.37	5.237	51.66	5.166	52.36	5.236	5.21
13.0	62.81	6.281	62.08	6.208	61.61	6.161	6.22
21.4	67.51	6.751	66	6.6	64.43	6.443	6.60
22.0	67.82	6.782	66.08	6.608	64.76	6.476	6.62
22.4	67.84	6.784	66.13	6.613	64.81	6.481	6.63

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – F40 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	7.64	0.764	8.39	0.839	10.31	1.031	0.88
0.8	12.84	1.284	13.48	1.348	15.99	1.599	1.41
1.0	16.15	1.615	16.74	1.674	19.85	1.985	1.76
1.9	25.54	2.554	27.52	2.752	31.94	3.194	2.83
2.0	26.97	2.697	28.65	2.865	32.85	3.285	2.95
2.0	27.73	2.773	29.63	2.963	33.95	3.395	3.04
5.1	46.28	4.628	49.14	4.914	58.66	5.866	5.14
6.8	52.32	5.232	55.15	5.515	66.3	6.63	5.79
13.0	58.90	5.89	62.23	6.223	74.16	7.416	6.51
21.4	63.91	6.391	67.2	6.72	78.85	7.885	7.00
22.0	64.09	6.409	67.27	6.727	79.25	7.925	7.02
22.4	64.09	6.409	67.61	6.761	79.55	7.955	7.04

SCC – TB – F60 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	11.17	1.117	11.9	1.19	9.55	0.955	1.09
0.8	18.15	1.815	18.35	1.835	14.35	1.435	1.70
1.0	22.52	2.252	22.4	2.24	17.63	1.763	2.08
1.9	37.42	3.742	34.15	3.415	27.61	2.761	3.31
2.0	39.21	3.921	35.55	3.555	28.25	2.825	3.43
2.0	40.34	4.034	36.19	3.619	28.93	2.893	3.52
5.1	61.42	6.142	55.3	5.53	44.58	4.458	5.38
6.8	66.71	6.671	60.11	6.011	48.93	4.893	5.86
13.0	71.74	7.174	64.38	6.438	51	5.1	6.24
21.4	75.79	7.579	66.79	6.679	55.93	5.593	6.62
22.0	75.82	7.582	66.81	6.681	55.93	5.593	6.62
22.4	76.15	7.615	66.96	6.696	55.99	5.599	6.64

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – F80 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	29.62	2.962	33.8	3.38	23.95	2.395	2.91
0.8	46.25	4.625	48.44	4.844	34.87	3.487	4.32
1.0	55.05	5.505	56.64	5.664	41.19	4.119	5.10
1.9	83.16	8.316	84.47	8.447	63.03	6.303	7.69
2.0	85.67	8.567	87.06	8.706	65.05	6.505	7.93
2.0	87.99	8.799	89.44	8.944	66.74	6.674	8.14
5.1	154.20	15.42	172.89	17.289	132.1	13.21	15.31
6.8	155.69	15.569	177.98	17.798	144.09	14.409	15.93
13.0	158.18	15.818	180.97	18.097	146.83	14.683	16.20
21.4	161.34	16.134	184.03	18.403	149.66	14.966	16.50
22.0	161.73	16.173	184.58	18.458	149.95	14.995	16.54
22.4	161.73	16.173	184.74	18.474	150.15	15.015	16.55

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – C (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	5.23	0.523	4.88	0.488	5.57	0.557	0.52
0.6	7.15	0.715	6.92	0.692	7.56	0.756	0.72
0.8	8.13	0.813	7.99	0.799	8.58	0.858	0.82
0.9	9.01	0.901	8.89	0.889	9.44	0.944	0.91
1.0	9.69	0.969	9.7	0.97	10.31	1.031	0.99
1.1	10.29	1.029	10.46	1.046	10.88	1.088	1.05
1.2	11.02	1.102	11.13	1.113	11.59	1.159	1.12
1.8	14.44	1.444	14.4	1.44	14.35	1.435	1.44
1.9	14.78	1.478	14.68	1.468	14.55	1.455	1.47
1.9	15.21	1.521	15.06	1.506	14.63	1.463	1.50
2.0	15.65	1.565	15.34	1.534	14.99	1.499	1.53
5.1	26.24	2.624	23.69	2.369	20.73	2.073	2.36
6.8	29.44	2.944	26.26	2.626	22.59	2.259	2.61
10.0	34.42	3.442	30.17	3.017	25.71	2.571	3.01
11.0	35.61	3.561	31.32	3.132	26.93	2.693	3.13
12.1	36.83	3.683	32.26	3.226	27.86	2.786	3.23
12.9	37.73	3.773	33.15	3.315	28.64	2.864	3.32
13.9	38.46	3.846	33.91	3.391	29.51	2.951	3.40
14.6	39.49	3.949	34.68	3.468	30.3	3.03	3.48
16.3	41.14	4.114	36.2	3.62	31.83	3.183	3.64
17.0	41.80	4.18	36.72	3.672	32.34	3.234	3.70
17.6	42.16	4.216	37.23	3.723	32.88	3.288	3.74
18.2	42.99	4.299	37.88	3.788	33.48	3.348	3.81
18.9	43.51	4.351	38.55	3.855	34.1	3.41	3.87
19.5	44.05	4.405	39.13	3.913	34.68	3.468	3.93
21.3	45.88	4.588	40.89	4.089	36.4	3.64	4.11
21.9	46.39	4.639	41.5	4.15	36.88	3.688	4.16
22.4	46.79	4.679	41.9	4.19	37.32	3.732	4.20

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	3.70	0.37	4.08	0.408	4.53	0.453	0.41
0.6	5.05	0.505	5.54	0.554	5.99	0.599	0.55
0.8	6.09	0.609	6.57	0.657	7.21	0.721	0.66
0.9	7.01	0.701	7.7	0.77	8.32	0.832	0.77
1.0	7.42	0.742	8.2	0.82	8.82	0.882	0.81
1.1	7.78	0.778	8.57	0.857	9.33	0.933	0.86
1.2	8.30	0.83	9.13	0.913	9.82	0.982	0.91
1.3	8.61	0.861	9.53	0.953	10.3	1.03	0.95
1.3	8.97	0.897	9.99	0.999	10.76	1.076	0.99
1.4	9.34	0.934	10.45	1.045	11.25	1.125	1.03
1.5	9.63	0.963	10.92	1.092	11.69	1.169	1.07
1.5	9.85	0.985	11.22	1.122	11.94	1.194	1.10
1.7	10.49	1.049	11.94	1.194	12.75	1.275	1.17
1.8	11.08	1.108	12.65	1.265	13.45	1.345	1.24
2.0	11.57	1.157	13.31	1.331	14.06	1.406	1.30
5.1	17.99	1.799	20.28	2.028	19.95	1.995	1.94
6.8	20.03	2.003	22.55	2.255	21.52	2.152	2.14
10.0	22.98	2.298	25.96	2.596	24.06	2.406	2.43
11.0	23.74	2.374	26.68	2.668	24.78	2.478	2.51
12.0	24.74	2.474	27.86	2.786	25.53	2.553	2.60
12.9	25.62	2.562	28.76	2.876	26.32	2.632	2.69
13.8	26.07	2.607	29.52	2.952	26.96	2.696	2.75
14.6	26.89	2.689	30.05	3.005	27.52	2.752	2.82
17.0	28.82	2.882	32.15	3.215	29.47	2.947	3.01
17.7	29.25	2.925	32.67	3.267	29.85	2.985	3.06
18.3	29.54	2.954	33.16	3.316	30.3	3.03	3.10
19.0	30.02	3.002	33.69	3.369	31.02	3.102	3.16
19.7	30.44	3.044	34.29	3.429	31.55	3.155	3.21
20.2	30.93	3.093	34.66	3.466	31.99	3.199	3.25
20.9	31.60	3.16	35.23	3.523	32.58	3.258	3.31
21.4	31.82	3.182	35.53	3.553	32.86	3.286	3.34
21.9	32.58	3.258	36.01	3.601	33.39	3.339	3.40
22.5	32.92	3.292	36.3	3.63	33.69	3.369	3.43

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G40 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	3.85	0.385	4.52	0.452	4.89	0.489	0.44
0.6	5.15	0.515	5.96	0.596	6.38	0.638	0.58
0.8	6.12	0.612	7.02	0.702	7.39	0.739	0.68
0.9	7.15	0.715	8.17	0.817	8.5	0.85	0.79
1.0	7.81	0.781	8.92	0.892	9.16	0.916	0.86
1.1	8.24	0.824	9.36	0.936	9.52	0.952	0.90
1.2	8.72	0.872	9.9	0.99	10.05	1.005	0.96
1.3	9.18	0.918	10.32	1.032	10.44	1.044	1.00
1.3	9.62	0.962	10.85	1.085	10.8	1.08	1.04
1.4	10.13	1.013	11.31	1.131	11.21	1.121	1.09
1.5	10.51	1.051	11.76	1.176	11.69	1.169	1.13
1.5	10.78	1.078	12.14	1.214	12.04	1.204	1.17
1.7	11.61	1.161	13.02	1.302	12.87	1.287	1.25
1.8	12.27	1.227	13.71	1.371	13.38	1.338	1.31
2.0	13.05	1.305	14.75	1.475	14.03	1.403	1.39
5.1	20.76	2.076	22.67	2.267	22.21	2.221	2.19
6.8	22.73	2.273	24.76	2.476	24.36	2.436	2.40
10.0	25.51	2.551	27.37	2.737	27.17	2.717	2.67
11.0	26.34	2.634	28.24	2.824	28.15	2.815	2.76
12.0	26.74	2.674	28.78	2.878	28.86	2.886	2.81
12.9	27.47	2.747	29.53	2.953	29.61	2.961	2.89
13.8	27.95	2.795	30.04	3.004	30.17	3.017	2.94
14.6	28.41	2.841	30.6	3.06	30.58	3.058	2.99
17.0	30.20	3.02	32.29	3.229	32.39	3.239	3.16
17.7	30.55	3.055	32.59	3.259	32.71	3.271	3.20
18.3	30.87	3.087	32.98	3.298	33.05	3.305	3.23
19.0	31.34	3.134	33.37	3.337	33.47	3.347	3.27
19.7	31.80	3.18	33.87	3.387	33.97	3.397	3.32
20.2	32.38	3.238	34.31	3.431	34.4	3.44	3.37
20.9	33.07	3.307	34.85	3.485	34.84	3.484	3.43
21.4	33.24	3.324	35.04	3.504	35.09	3.509	3.45
21.9	33.84	3.384	35.62	3.562	35.7	3.57	3.51
22.5	34.27	3.427	35.97	3.597	35.92	3.592	3.54

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G60 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	3.46	0.346	3.18	0.318	3.25	0.325	0.33
0.7	5.14	0.514	4.69	0.469	4.94	0.494	0.49
0.9	7.14	0.714	5.81	0.581	5.58	0.558	0.62
1.0	7.35	0.735	6.56	0.656	6.08	0.608	0.67
1.1	8.12	0.812	7.15	0.715	6.54	0.654	0.73
1.5	10.86	1.086	9.98	0.998	8.72	0.872	0.99
1.6	11.47	1.147	10.38	1.038	9.18	0.918	1.03
1.7	11.78	1.178	10.8	1.08	9.56	0.956	1.07
1.7	12.17	1.217	11.12	1.112	9.72	0.972	1.10
1.8	12.55	1.255	11.4	1.14	10.17	1.017	1.14
1.8	13.04	1.304	11.78	1.178	10.41	1.041	1.17
1.9	13.23	1.323	12.07	1.207	10.74	1.074	1.20
2.0	13.67	1.367	12.29	1.229	10.92	1.092	1.23
5.0	28.17	2.817	26.56	2.656	24.07	2.407	2.63
7.0	33.70	3.37	32.56	3.256	30.41	3.041	3.22
11.1	38.97	3.897	39.89	3.989	39.74	3.974	3.95
12.1	39.49	3.949	40.7	4.07	41.17	4.117	4.05
13.0	40.09	4.009	41.38	4.138	42.32	4.232	4.13
14.0	40.84	4.084	42.17	4.217	43.59	4.359	4.22
14.9	41.39	4.139	42.74	4.274	44.63	4.463	4.29
15.6	42.42	4.242	43.14	4.314	45.43	4.543	4.37
16.4	42.94	4.294	43.81	4.381	46.24	4.624	4.43
17.1	43.22	4.322	44.15	4.415	46.71	4.671	4.47
17.7	43.70	4.37	44.62	4.462	47.49	4.749	4.53
18.4	44.16	4.416	45.04	4.504	47.93	4.793	4.57
19.1	44.31	4.431	45.37	4.537	48.31	4.831	4.60
19.7	44.83	4.483	45.7	4.57	48.77	4.877	4.64
20.5	45.24	4.524	46.32	4.632	49.49	4.949	4.70
20.9	45.61	4.561	46.65	4.665	49.87	4.987	4.74
21.5	45.80	4.58	46.78	4.678	49.96	4.996	4.75
22.0	46.12	4.612	47.1	4.71	50.45	5.045	4.79
22.4	46.36	4.636	47.27	4.727	50.63	5.063	4.81

SCC – G80 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	3.64	0.364	2.97	0.297	3.79	0.379	0.35
0.7	5.36	0.536	4.17	0.417	5.13	0.513	0.49
0.9	6.64	0.664	5.02	0.502	6.38	0.638	0.60
1.0	7.32	0.732	5.6	0.56	7.1	0.71	0.67
1.1	7.90	0.79	6.09	0.609	7.74	0.774	0.72
1.5	10.44	1.044	7.94	0.794	10.51	1.051	0.96
1.6	10.97	1.097	8.35	0.835	11.07	1.107	1.01
1.7	11.50	1.15	8.55	0.855	11.24	1.124	1.04
1.7	12.06	1.206	8.82	0.882	11.46	1.146	1.08
1.8	12.60	1.26	9.24	0.924	11.97	1.197	1.13
1.8	13.21	1.321	9.55	0.955	12.29	1.229	1.17
1.9	13.78	1.378	9.76	0.976	12.61	1.261	1.20
2.0	13.95	1.395	9.8	0.98	12.79	1.279	1.22
5.0	27.91	2.791	18.35	1.835	24.04	2.404	2.34
7.0	33.50	3.35	21.76	2.176	28.15	2.815	2.78
11.1	40.38	4.038	25.82	2.582	33.29	3.329	3.32
12.1	40.68	4.068	26.18	2.618	33.71	3.371	3.35
13.0	41.40	4.14	26.73	2.673	34.28	3.428	3.41
14.0	42.02	4.202	27.38	2.738	34.84	3.484	3.47
14.9	42.99	4.299	28.05	2.805	35.56	3.556	3.55
15.6	43.58	4.358	28.66	2.866	36.13	3.613	3.61
16.4	44.29	4.429	29.26	2.926	36.54	3.654	3.67
17.1	44.58	4.458	29.55	2.955	36.87	3.687	3.70
17.7	45.12	4.512	30.1	3.01	37.38	3.738	3.75
18.4	45.62	4.562	30.55	3.055	37.85	3.785	3.80
19.1	46.17	4.617	31.04	3.104	38.32	3.832	3.85
19.7	46.74	4.674	31.56	3.156	38.89	3.889	3.91
20.5	47.51	4.751	32.27	3.227	39.51	3.951	3.98
20.9	47.80	4.78	32.43	3.243	39.77	3.977	4.00
21.5	47.98	4.798	32.85	3.285	40.11	4.011	4.03
22.0	48.30	4.83	33.32	3.332	40.51	4.051	4.07
22.4	48.64	4.864	33.61	3.361	40.8	4.08	4.10

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area** $(\mathbf{Kg/m^2})$
Time $(\mathbf{h^{0.5}})$	**Water intake (g)**	**Water intake/unit area** $(\mathbf{Kg/m^2})$	**Water intake (g)**	**Water intake/unit area** $(\mathbf{Kg/m^2})$	**Water intake (g)**	**Water intake/unit area** $(\mathbf{Kg/m^2})$	
0.0	0.00	0	0	0	0	0	0.00
0.4	4.83	0.483	4.33	0.433	3.9	0.39	0.44
0.6	6.34	0.634	5.75	0.575	5.2	0.52	0.58
0.8	8.09	0.809	6.99	0.699	6.51	0.651	0.72
0.9	9.13	0.913	7.91	0.791	7.44	0.744	0.82
1.0	9.90	0.99	8.59	0.859	8.2	0.82	0.89
1.1	10.83	1.083	9.39	0.939	8.91	0.891	0.97
1.6	14.47	1.447	12.35	1.235	11.92	1.192	1.29
1.7	15.23	1.523	13.03	1.303	12.6	1.26	1.36
1.8	15.51	1.551	13.12	1.312	12.78	1.278	1.38
1.8	15.99	1.599	13.47	1.347	13.09	1.309	1.42
1.9	16.26	1.626	13.66	1.366	13.31	1.331	1.44
1.9	16.51	1.651	13.86	1.386	13.42	1.342	1.46
2.0	17.09	1.709	14.13	1.413	13.78	1.378	1.50
5.4	31.92	3.192	22.09	2.209	21.95	2.195	2.53
7.3	36.19	3.619	24.42	2.442	22.94	2.294	2.78
8.7	38.44	3.844	25.9	2.59	24.18	2.418	2.95
10.1	40.03	4.003	26.99	2.699	25.29	2.529	3.08
11.1	40.80	4.08	27.89	2.789	26.18	2.618	3.16
12.0	41.74	4.174	28.79	2.879	26.86	2.686	3.25
13.1	43.20	4.32	29.69	2.969	27.68	2.768	3.35
14.0	44.28	4.428	30.5	3.05	28.46	2.846	3.44
14.8	44.74	4.474	31.14	3.114	29.21	2.921	3.50
15.9	45.15	4.515	31.87	3.187	29.78	2.978	3.56
16.4	45.61	4.561	32.33	3.233	30.6	3.06	3.62
17.1	46.58	4.658	32.87	3.287	30.97	3.097	3.68
17.8	47.39	4.739	33.35	3.335	31.47	3.147	3.74
18.3	47.59	4.759	33.74	3.374	31.85	3.185	3.77
19.0	47.81	4.781	34.32	3.432	32.45	3.245	3.82
19.6	48.32	4.832	34.76	3.476	32.98	3.298	3.87
20.3	48.92	4.892	35.33	3.533	33.51	3.351	3.93
20.8	49.25	4.925	35.78	3.578	33.96	3.396	3.97
21.5	49.72	4.972	36.1	3.61	34.38	3.438	4.01
22.0	50.01	5.001	36.65	3.665	34.93	3.493	4.05
22.7	50.50	5.05	37.08	3.708	35.3	3.53	4.096

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F40 (28 days)

Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	7.84	0.784	7.95	0.795	7.89	0.789	0.79
0.6	10.05	1.005	10.05	1.005	9.95	0.995	1.00
0.8	11.43	1.143	11.16	1.116	11.48	1.148	1.14
0.9	12.56	1.256	12.22	1.222	12.56	1.256	1.24
1.5	15.64	1.564	15.13	1.513	16.09	1.609	1.56
1.7	16.33	1.633	15.87	1.587	17.07	1.707	1.64
1.8	16.88	1.688	16.39	1.639	17.65	1.765	1.70
1.9	17.32	1.732	16.87	1.687	18.38	1.838	1.75
5.1	27.54	2.754	27.35	2.735	30.89	3.089	2.86
7.1	32.37	3.237	32.18	3.218	36.15	3.615	3.36
8.7	34.32	3.432	35.51	3.551	38.39	3.839	3.61
12.1	40.17	4.017	41.85	4.185	44.74	4.474	4.23
13.1	42.37	4.237	44.2	4.42	46.56	4.656	4.44
14.1	43.87	4.387	45.7	4.57	48.06	4.806	4.59
14.9	45.02	4.502	46.85	4.685	49.21	4.921	4.70
15.7	45.87	4.587	47.7	4.77	50.06	5.006	4.79
18.7	47.97	4.797	49.8	4.98	52.16	5.216	5.00
19.3	48.37	4.837	50.2	5.02	52.56	5.256	5.04
19.9	48.77	4.877	50.6	5.06	52.96	5.296	5.08
20.5	49.17	4.917	51	5.1	53.36	5.336	5.12
21.1	49.42	4.942	51.25	5.125	53.61	5.361	5.14
21.6	49.67	4.967	51.5	5.15	53.86	5.386	5.17
22.2	50.02	5.002	51.85	5.185	54.21	5.421	5.20
22.7	50.32	5.032	52.15	5.215	54.51	5.451	5.23

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F60 (28 days)

Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	10.94	1.094	12.93	1.293	13.55	1.355	1.25
0.6	13.25	1.325	16.17	1.617	16.93	1.693	1.55
0.8	14.79	1.479	18.27	1.827	19.73	1.973	1.76
0.9	15.84	1.584	20.27	2.027	21.47	2.147	1.92
1.5	19.28	1.928	25.58	2.558	28.19	2.819	2.43
1.7	20.15	2.015	26.92	2.692	29.88	2.988	2.56
1.8	20.69	2.069	27.84	2.784	30.89	3.089	2.65
1.9	21.32	2.132	28.68	2.868	32.39	3.239	2.75
5.1	32.46	3.246	43.75	4.375	53.35	5.335	4.32
7.1	39.49	3.949	52.93	5.293	64.4	6.44	5.23
8.7	43.01	4.301	57.99	5.799	70.95	7.095	5.73
12.1	50.67	5.067	61.19	6.119	81.95	8.195	6.46
13.1	55.72	5.572	71.38	7.138	87.76	8.776	7.16
14.1	58.22	5.822	75.31	7.531	92.47	9.247	7.53
14.9	59.22	5.922	76.31	7.631	93.47	9.347	7.63
15.7	59.96	5.996	77.01	7.701	95.11	9.511	7.74
18.7	65.09	6.509	82.67	8.267	99.31	9.931	8.24
19.3	66.08	6.608	83.67	8.367	100.31	10.031	8.34
19.9	66.53	6.653	84.12	8.412	100.76	10.076	8.38
20.5	66.93	6.693	84.52	8.452	101.16	10.116	8.42

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F80 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	17.46	1.746	18.83	1.883	19.48	1.948	1.86
0.6	22.4	2.24	23.89	2.389	25.46	2.546	2.39
0.8	26.12	2.612	27.6	2.76	28.98	2.898	2.76
0.9	28.72	2.872	30.16	3.016	31.58	3.158	3.02
1.5	38.12	3.812	39.07	3.907	40.95	4.095	3.94
1.7	40.66	4.066	41.22	4.122	43.84	4.384	4.19
1.8	42.16	4.216	42.71	4.271	45.51	4.551	4.35
1.9	44.03	4.403	44.21	4.421	47.37	4.737	4.52
5.1	85.02	8.502	78.31	7.831	84.54	8.454	8.26
7.1	113.48	11.348	102.69	10.269	108.1	10.81	10.81
8.7	132.37	13.237	121.1	12.11	125	12.5	12.62
12.1	166.54	16.654	146.58	14.658	152.86	15.286	15.53
13.1	169.37	16.937	148.94	14.894	155.01	15.501	15.78
14.1	170.12	17.012	149.69	14.969	155.76	15.576	15.85
14.9	170.72	17.072	150.29	15.029	156.36	15.636	15.91
15.7	171.12	17.112	150.94	15.094	156.98	15.698	15.97
18.7	172.12	17.212	151.44	15.144	157.43	15.743	16.03
19.3	172.52	17.252	151.94	15.194	157.88	15.788	16.08
19.9	172.92	17.292	152.44	15.244	158.33	15.833	16.12
20.5	173.12	17.312	152.94	15.294	158.78	15.878	16.16
21.1	173.32	17.332	153.19	15.319	158.98	15.898	16.18
21.6	173.52	17.352	153.44	15.344	159.18	15.918	16.20
22.2	173.72	17.372	153.69	15.369	159.38	15.938	16.23
22.7	173.92	17.392	153.94	15.394	159.53	15.953	16.25

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – L10 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	10.52	1.052	12.33	1.233	10.04	1.004	1.10
0.6	12.88	1.288	14.77	1.477	12.66	1.266	1.34
0.8	14.85	1.485	16.67	1.667	14.64	1.464	1.54
0.9	16.42	1.642	18.3	1.83	16.31	1.631	1.70
1.5	23.27	2.327	24.76	2.476	23.32	2.332	2.38
1.7	25.66	2.566	26.68	2.668	25.12	2.512	2.58
1.8	26.96	2.696	27.97	2.797	26.47	2.647	2.71
1.9	28.49	2.849	29.11	2.911	27.67	2.767	2.84
5.1	57.9	5.79	57.06	5.706	59.24	5.924	5.81
7.1	71.52	7.152	70.86	7.086	75.55	7.555	7.26
8.7	81.075	8.1075	81.61	8.161	85.53	8.553	8.27
12.1	94.07	9.407	97.88	9.788	101.73	10.173	9.79
13.1	96.57	9.657	101.13	10.113	105.23	10.523	10.10
14.1	97.32	9.732	102.63	10.263	106.73	10.673	10.22
14.9	97.82	9.782	103.13	10.313	107.23	10.723	10.27
15.7	98.82	9.882	104.33	10.433	108.43	10.843	10.39
18.7	100.32	10.032	105.93	10.593	110.23	11.023	10.55
19.3	101.07	10.107	106.43	10.643	111.03	11.103	10.62
19.9	101.67	10.167	107.13	10.713	111.48	11.148	10.68
20.5	101.77	10.177	107.38	10.738	111.6	11.16	10.69

SCC – L20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	6.73	0.673	7.94	0.794	8.87	0.887	0.78
0.6	8.87	0.887	10.45	1.045	11.36	1.136	1.02
0.8	10.66	1.066	12.65	1.265	13.64	1.364	1.23
0.9	11.89	1.189	13.99	1.399	14.79	1.479	1.36
1.0	13.29	1.329	15.51	1.551	16.17	1.617	1.50
1.6	20.62	2.062	23.29	2.329	23.91	2.391	2.26
1.7	22.00	2.2	24.48	2.448	25.06	2.506	2.38
1.8	22.71	2.271	25.19	2.519	25.49	2.549	2.45
1.9	24.04	2.404	26.24	2.624	26.84	2.684	2.57
2.0	25.37	2.537	27.34	2.734	28.1	2.81	2.69
5.5	63.12	6.312	61.15	6.115	60.21	6.021	6.15
7.2	77.74	7.774	75.29	7.529	72.82	7.282	7.53
8.8	88.00	8.8	85.14	8.514	81.53	8.153	8.49
10.1	95.64	9.564	91.7	9.17	87.19	8.719	9.15
11.2	101.13	10.113	96.64	9.664	91.74	9.174	9.65
12.0	104.38	10.438	99.73	9.973	94.7	9.47	9.96
13.2	107.54	10.754	103.7	10.37	98.72	9.872	10.33
14.1	110.09	11.009	106.42	10.642	101.57	10.157	10.60
14.8	110.23	11.023	106.7	10.67	101.8	10.18	10.62
15.7	112.93	11.293	109.92	10.992	105.25	10.525	10.94
16.4	114.25	11.425	111.46	11.146	107.15	10.715	11.10
17.1	114.98	11.498	112.7	11.27	108.29	10.829	11.20
17.7	115.65	11.565	113.62	11.362	109.55	10.955	11.29
18.4	116.37	11.637	114.51	11.451	110.89	11.089	11.39
19.1	117.05	11.705	115.39	11.539	112.06	11.206	11.48
19.6	117.44	11.744	115.97	11.597	113.01	11.301	11.55
20.3	117.93	11.793	116.67	11.667	114.46	11.446	11.64
20.9	118.43	11.843	117.17	11.717	114.96	11.496	11.69
21.4	118.93	11.893	117.67	11.767	115.46	11.546	11.74
22.0	119.43	11.943	118.17	11.817	115.96	11.596	11.79
22.5	119.93	11.993	118.67	11.867	116.46	11.646	11.84

SCC – L30 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	6.17	0.617	5.38	0.538	5.85	0.585	0.58
0.6	8.04	0.804	6.71	0.671	7.37	0.737	0.74
0.8	9.23	0.923	7.98	0.798	8.83	0.883	0.87
0.9	10.58	1.058	9	0.9	9.74	0.974	0.98
1.0	11.77	1.177	9.8	0.98	11	1.1	1.09
1.6	18.09	1.809	14.4	1.44	16.33	1.633	1.63
1.7	19.00	1.9	14.99	1.499	17.33	1.733	1.71
1.8	19.54	1.954	15.45	1.545	17.74	1.774	1.76
1.9	20.56	2.056	16.26	1.626	18.83	1.883	1.85
2.0	21.66	2.166	16.99	1.699	19.68	1.968	1.94
5.5	52.72	5.272	36.9	3.69	45.98	4.598	4.52
7.2	66.93	6.693	45.47	4.547	57.38	5.738	5.66
8.8	77.34	7.734	51.7	5.17	65.46	6.546	6.48
10.1	84.38	8.438	56.07	5.607	70.73	7.073	7.04
11.2	89.79	8.979	59.9	5.99	75.14	7.514	7.49
12.0	93.05	9.305	62.45	6.245	77.83	7.783	7.78
13.2	97.09	9.709	65.63	6.563	81.54	8.154	8.14
14.1	100.08	10.008	68.32	6.832	84.54	8.454	8.43
14.8	100.28	10.028	68.5	6.85	84.74	8.474	8.45
15.7	103.64	10.364	71.89	7.189	88.27	8.827	8.79
16.4	105.04	10.504	73.4	7.34	90.11	9.011	8.95
17.1	106.04	10.604	74.59	7.459	91.84	9.184	9.08
17.7	106.94	10.694	75.64	7.564	92.84	9.284	9.18
18.4	107.70	10.77	76.74	7.674	94.01	9.401	9.28
19.1	108.63	10.863	77.92	7.792	95.45	9.545	9.40
19.6	109.06	10.906	78.38	7.838	95.84	9.584	9.44
20.3	109.50	10.95	79.18	7.918	96.91	9.691	9.52
20.9	110.00	11	79.68	7.968	97.26	9.726	9.56
21.4	110.50	11.05	80.18	8.018	97.61	9.761	9.61
22.0	111.00	11.1	80.68	8.068	97.96	9.796	9.65
22.5	111.50	11.15	81.18	8.118	98.31	9.831	9.70

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – G20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	7.57	0.757	6.45	0.645	7.5	0.75	0.72
0.8	11.35	1.135	9.38	0.938	10.46	1.046	1.04
1.0	14.22	1.422	11.49	1.149	12.53	1.253	1.27
1.9	23.78	2.378	20.64	2.064	20.28	2.028	2.16
2.0	24.98	2.498	21.43	2.143	20.88	2.088	2.24
2.0	25.94	2.594	22.72	2.272	21.58	2.158	2.34
5.1	45.55	4.555	44	4.4	40.29	4.029	4.33
6.8	52.02	5.202	51.78	5.178	46.94	4.694	5.02
13.0	62.06	6.206	66.4	6.64	57.3	5.73	6.19
21.4	68.74	6.874	76.69	7.669	65.08	6.508	7.02
22.0	69.60	6.96	76.83	7.683	65.43	6.543	7.06
22.4	69.99	6.999	77.57	7.757	65.81	6.581	7.11

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – G40 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	5.19	0.519	4.73	0.473	4.87	0.487	0.49
0.8	8.19	0.819	7.41	0.741	6.88	0.688	0.75
1.0	9.97	0.997	8.91	0.891	8.16	0.816	0.90
1.9	15.29	1.529	14.35	1.435	12.96	1.296	1.42
2.0	16.44	1.644	14.74	1.474	13.32	1.332	1.48
2.0	17.27	1.727	15.22	1.522	13.76	1.376	1.54
5.1	31.10	3.11	29.34	2.934	25.49	2.549	2.86
6.8	36.45	3.645	34.03	3.403	29.49	2.949	3.33
13.0	45.75	4.575	41.5	4.15	35.89	3.589	4.10
21.4	53.37	5.337	47.81	4.781	41.12	4.112	4.74
22.0	54.80	5.48	47.98	4.798	41.72	4.172	4.82
22.4	55.44	5.544	48.36	4.836	42.06	4.206	4.86

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – G60 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	4.60	0.46	4.76	0.476	5.45	0.545	0.49
0.8	6.52	0.652	6.5	0.65	7.12	0.712	0.67
1.0	7.54	0.754	7.6	0.76	8.29	0.829	0.78
1.9	11.27	1.127	11.53	1.153	12.64	1.264	1.18
2.0	11.84	1.184	11.79	1.179	13.03	1.303	1.22
2.0	12.26	1.226	12.13	1.213	13.39	1.339	1.26
5.1	23.92	2.392	24.15	2.415	25.17	2.517	2.44
6.8	28.74	2.874	28.99	2.899	29.69	2.969	2.91
13.0	38.29	3.829	37.08	3.708	39.61	3.961	3.83
21.4	44.22	4.422	42.35	4.235	46.82	4.682	4.45
22.0	45.49	4.549	42.99	4.299	47.65	4.765	4.54
22.4	46.08	4.608	43.42	4.342	47.85	4.785	4.58

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – G80 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.6	8.62	0.862	7.89	0.789	7.74	0.774	0.81
0.9	11.31	1.131	10.27	1.027	10.14	1.014	1.06
1.0	12.98	1.298	12.22	1.222	12.1	1.21	1.24
1.9	18.66	1.866	18.27	1.827	18.29	1.829	1.84
2.0	19.39	1.939	18.78	1.878	18.82	1.882	1.90
2.1	19.75	1.975	19.44	1.944	19.32	1.932	1.95
5.1	35.16	3.516	35.81	3.581	36.95	3.695	3.60
6.8	40.49	4.049	41.75	4.175	42.6	4.26	4.16
13.0	51.14	5.114	54.56	5.456	52.97	5.297	5.29
21.4	54.33	5.433	61.37	6.137	59.66	5.966	5.85
22.0	54.98	5.498	61.91	6.191	60.75	6.075	5.92
22.4	54.98	5.498	62.24	6.224	60.77	6.077	5.93

SCC – TB – F20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	1.07	0.107	1.13	0.113	1.6	0.16	0.13
1.7	8.14	0.814	8.12	0.812	10.2	1.02	0.88
2.0	10.30	1.03	9.77	0.977	11.85	1.185	1.06
5.2	29.01	2.901	25.77	2.577	31.46	3.146	2.87
7.1	36.63	3.663	31.82	3.182	39.75	3.975	3.61
8.6	40.67	4.067	35.55	3.555	44.69	4.469	4.03
10.0	43.48	4.348	37.64	3.764	48.18	4.818	4.31
11.1	45.48	4.548	39.84	3.984	50.65	5.065	4.53
12.1	46.65	4.665	40.86	4.086	52.05	5.205	4.65
14.1	48.37	4.837	42.24	4.224	54.05	5.405	4.82
14.9	49.40	4.94	43.47	4.347	55.62	5.562	4.95
15.7	50.02	5.002	44.26	4.426	56.42	5.642	5.02
16.5	50.56	5.056	44.91	4.491	57.04	5.704	5.08
18.4	51.73	5.173	45.84	4.584	58.09	5.809	5.19
20.7	52.75	5.275	46.53	4.653	58.95	5.895	5.27
24.5	53.56	5.356	47.06	4.706	59.75	5.975	5.35

SCC – TB – F40 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	1.50	0.15	1.54	0.154	0.81	0.081	0.13
1.7	13.92	1.392	8.29	0.829	7.58	0.758	0.99
2.0	15.81	1.581	10	1	9.22	0.922	1.17
5.2	37.70	3.77	27.56	2.756	26.51	2.651	3.06
7.1	46.68	4.668	35.86	3.586	34.28	3.428	3.89
8.6	51.98	5.198	41.31	4.131	39.19	3.919	4.42
10.0	56.29	5.629	45.72	4.572	42.88	4.288	4.83
11.1	59.08	5.908	49.45	4.945	46	4.6	5.15
12.1	60.37	6.037	51.82	5.182	47.85	4.785	5.33
14.1	63.24	6.324	56.38	5.638	51.5	5.15	5.70
14.9	64.91	6.491	58.95	5.895	53.27	5.327	5.90
15.7	66.03	6.603	60.57	6.057	54.8	5.48	6.05
16.5	66.89	6.689	62.44	6.244	56.01	5.601	6.18
18.4	68.47	6.847	65.84	6.584	58.5	5.85	6.43
20.7	69.70	6.97	68.64	6.864	60.53	6.053	6.63
24.5	71.75	7.175	73.58	7.358	63.87	6.387	6.97

SCC – TB – F60 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	2.65	0.265	4.18	0.418	1.52	0.152	0.28
1.7	10.67	1.067	12.94	1.294	11.66	1.166	1.18
2.0	11.93	1.193	14.17	1.417	13.15	1.315	1.31
5.2	23.71	2.371	26.79	2.679	26.3	2.63	2.56
7.1	29.11	2.911	32.02	3.202	31.46	3.146	3.09
8.6	31.93	3.193	34.95	3.495	34.54	3.454	3.38
10.0	33.77	3.377	36.94	3.694	36.82	3.682	3.58
11.1	35.67	3.567	39.09	3.909	38.66	3.866	3.78
12.1	36.73	3.673	39.81	3.981	39.57	3.957	3.87
14.1	38.10	3.81	41.34	4.134	41.18	4.118	4.02
14.9	39.72	3.972	42.51	4.251	42.39	4.239	4.15
15.7	40.45	4.045	43.25	4.325	43.28	4.328	4.23
16.5	41.14	4.114	44.18	4.418	43.86	4.386	4.31
18.4	42.62	4.262	45.65	4.565	45.48	4.548	4.46
20.7	43.91	4.391	46.59	4.659	46.33	4.633	4.56
24.5	45.99	4.599	48.67	4.867	48.87	4.887	4.78

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – F80 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	4.29	0.429	6.11	0.611	9.23	0.923	0.65
1.7	30.32	3.032	34.72	3.472	35.94	3.594	3.37
2.0	34.60	3.46	39.04	3.904	40.22	4.022	3.80
5.2	81.35	8.135	84.8	8.48	89.26	8.926	8.51
7.1	107.44	10.744	110.3	11.03	115.71	11.571	11.12
8.6	126.95	12.695	126.85	12.685	132.01	13.201	12.86
10.0	139.27	13.927	134.95	13.495	139.73	13.973	13.80
11.1	144.25	14.425	138.79	13.879	142.14	14.214	14.17
12.1	145.91	14.591	139.6	13.96	142.42	14.242	14.26
14.1	147.28	14.728	140.3	14.03	143.52	14.352	14.37
14.9	148.22	14.822	141.28	14.128	143.94	14.394	14.45
15.7	149.48	14.948	141.78	14.178	144.34	14.434	14.52
16.5	149.77	14.977	141.96	14.196	144.72	14.472	14.55
18.4	149.99	14.999	143.02	14.302	145.19	14.519	14.61
20.7	151.00	15.1	143.81	14.381	146.14	14.614	14.70
24.5	152.12	15.212	144.47	14.447	147.21	14.721	14.79

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – C (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	4.18	0.418	4.25	0.425	5.4	0.54	0.46
0.6	5.33	0.533	5.2	0.52	6.51	0.651	0.57
0.8	6.65	0.665	6.5	0.65	8.18	0.818	0.71
0.9	7.07	0.707	6.86	0.686	8.53	0.853	0.75
1.0	7.44	0.744	7.41	0.741	9.37	0.937	0.81
1.1	8.16	0.816	8.08	0.808	10.02	1.002	0.88
1.4	10.01	1.001	9.56	0.956	12.06	1.206	1.05
1.5	10.29	1.029	9.97	0.997	12.34	1.234	1.09
1.5	10.66	1.066	10.11	1.011	12.81	1.281	1.12
1.6	11.07	1.107	10.31	1.031	13.16	1.316	1.15
1.7	11.30	1.13	11.02	1.102	13.56	1.356	1.20
1.7	11.65	1.165	11.17	1.117	13.9	1.39	1.22
1.8	12.33	1.233	11.6	1.16	14.69	1.469	1.29
1.9	12.63	1.263	12.05	1.205	15.03	1.503	1.32
4.9	22.65	2.265	21.23	2.123	26.1	2.61	2.33
6.9	25.74	2.574	25.26	2.526	29.06	2.906	2.67
8.5	27.26	2.726	27.59	2.759	30.22	3.022	2.84
10.0	28.58	2.858	29.81	2.981	31.44	3.144	2.99
11.1	30.24	3.024	31.78	3.178	32.53	3.253	3.15
12.0	30.68	3.068	32.87	3.287	33.07	3.307	3.22
13.0	31.54	3.154	34.03	3.403	33.83	3.383	3.31
13.9	31.75	3.175	35.19	3.519	34.15	3.415	3.37
15.4	33.02	3.302	37.07	3.707	35.11	3.511	3.51
17.1	34.25	3.425	38.88	3.888	36.29	3.629	3.65
18.3	35.32	3.532	40.34	4.034	37.08	3.708	3.76
19.0	35.47	3.547	40.78	4.078	37.49	3.749	3.79
19.6	36.14	3.614	41.15	4.115	37.87	3.787	3.84
20.0	36.61	3.661	42.07	4.207	38.4	3.84	3.90
20.6	36.90	3.69	42.27	4.227	38.6	3.86	3.93
21.3	37.17	3.717	42.62	4.262	38.74	3.874	3.95
22.9	37.53	3.753	43.35	4.335	39.33	3.933	4.01

SCC – G20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	3.96	0.396	4.94	0.494	4.54	0.454	0.45
0.6	5.88	0.588	6.88	0.688	6.5	0.65	0.64
0.8	7.16	0.716	8.11	0.811	7.7	0.77	0.77
0.9	7.94	0.794	9.3	0.93	8.61	0.861	0.86
1.5	9.96	0.996	12.37	1.237	11.48	1.148	1.13
1.7	10.74	1.074	13.25	1.325	12.29	1.229	1.21
1.8	11.02	1.102	13.97	1.397	13.34	1.334	1.28
1.9	11.47	1.147	14.38	1.438	13.78	1.378	1.32
5.1	18.4	1.84	25.6	2.56	22.35	2.235	2.21
7.1	20.76	2.076	31.54	3.154	25.86	2.586	2.61
8.7	22.03	2.203	32.53	3.253	26.84	2.684	2.71
12.1	23.82	2.382	34.46	3.446	28.64	2.864	2.90
13.1	24.77	2.477	35.41	3.541	29.59	2.959	2.99
14.1	25.62	2.562	36.26	3.626	30.44	3.044	3.08
14.9	26.27	2.627	36.91	3.691	31.09	3.109	3.14
15.7	26.89	2.689	37.53	3.753	31.71	3.171	3.20
18.7	28.64	2.864	39.28	3.928	33.46	3.346	3.38
19.3	29.34	2.934	39.98	3.998	34.16	3.416	3.45
19.9	29.94	2.994	40.58	4.058	34.76	3.476	3.51
20.5	30.49	3.049	41.13	4.113	35.31	3.531	3.56
21.1	30.84	3.084	41.48	4.148	35.66	3.566	3.60
21.6	31.26	3.126	41.9	4.19	36.08	3.608	3.64
22.2	31.51	3.151	42.15	4.215	36.33	3.633	3.67
22.7	31.76	3.176	42.4	4.24	36.58	3.658	3.69

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G40 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	4.5	0.45	5.03	0.503	3.83	0.383	0.45
0.6	6.45	0.645	7.08	0.708	5.24	0.524	0.63
0.8	8.05	0.805	8.19	0.819	6.15	0.615	0.75
0.9	9.51	0.951	9.1	0.91	6.84	0.684	0.85
1.5	12.19	1.219	12.12	1.212	9.23	0.923	1.12
1.7	12.96	1.296	12.82	1.282	10.09	1.009	1.20
1.8	13.48	1.348	13.34	1.334	10.57	1.057	1.25
1.9	13.9	1.39	13.76	1.376	10.9	1.09	1.29
5.1	27.02	2.702	25.75	2.575	23.37	2.337	2.54
7.1	33.88	3.388	32.35	3.235	29.63	2.963	3.20
8.7	35.79	3.579	35.11	3.511	31.9	3.19	3.43
12.1	41.87	4.187	41.98	4.198	39.29	3.929	4.10
13.1	43.37	4.337	43.48	4.348	40.79	4.079	4.25
14.1	44.37	4.437	44.48	4.448	41.79	4.179	4.35
14.9	45.02	4.502	45.13	4.513	42.44	4.244	4.42
15.7	45.97	4.597	46.08	4.608	43.39	4.339	4.51
18.7	47.47	4.747	47.58	4.758	44.89	4.489	4.66
19.3	47.99	4.799	48.1	4.81	45.41	4.541	4.72
19.9	48.39	4.839	48.5	4.85	45.81	4.581	4.76
20.5	49.01	4.901	49.12	4.912	46.43	4.643	4.82
21.1	49.34	4.934	49.45	4.945	46.76	4.676	4.85
21.6	49.62	4.962	49.73	4.973	47.04	4.704	4.88
22.2	49.87	4.987	49.98	4.998	47.29	4.729	4.90
22.7	50.12	5.012	50.23	5.023	47.54	4.754	4.93

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G60 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time $(h^{0.5})$	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	4.8	0.48	4.91	0.491	4.52	0.452	0.47
0.6	6.17	0.617	6.41	0.641	5.89	0.589	0.62
0.8	7.84	0.784	7.32	0.732	6.52	0.652	0.72
0.9	8.5	0.85	8.09	0.809	7.43	0.743	0.80
1.5	10.51	1.051	10.01	1.001	9.38	0.938	1.00
1.7	11.31	1.131	10.52	1.052	10.27	1.027	1.07
1.8	11.7	1.17	11.05	1.105	10.62	1.062	1.11
1.9	11.91	1.191	11.17	1.117	11.02	1.102	1.14
5.1	20.31	2.031	19.14	1.914	19.97	1.997	1.98
7.1	25.03	2.503	22.98	2.298	24.81	2.481	2.43
8.7	26.76	2.676	25.03	2.503	27.23	2.723	2.63
12.1	32.18	3.218	28.95	2.895	33.52	3.352	3.16
13.1	35.71	3.571	31.91	3.191	37.43	3.743	3.50
14.1	37.62	3.762	33.72	3.372	38.78	3.878	3.67
14.9	38.37	3.837	34.37	3.437	39.43	3.943	3.74
15.7	39.12	3.912	35.02	3.502	40.08	4.008	3.81
18.7	41.72	4.172	37.22	3.722	42.88	4.288	4.06
19.3	42.22	4.222	37.72	3.772	43.38	4.338	4.11
19.9	42.72	4.272	38.22	3.822	43.88	4.388	4.16
20.5	43.22	4.322	38.72	3.872	44.38	4.438	4.21
21.1	43.72	4.372	39.22	3.922	44.88	4.488	4.26
21.6	44.12	4.412	39.62	3.962	45.28	4.528	4.30
22.2	44.52	4.452	40.02	4.002	45.68	4.568	4.34
22.7	44.92	4.492	40.42	4.042	46.08	4.608	4.38

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – G80 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	4.32	0.432	5.2	0.52	4.8	0.48	0.48
0.6	5.9	0.59	6.82	0.682	6.13	0.613	0.63
0.8	7.09	0.709	7.96	0.796	7.04	0.704	0.74
0.9	8.12	0.812	9.05	0.905	7.9	0.79	0.84
1.5	11.11	1.111	12.33	1.233	10.52	1.052	1.13
1.7	11.79	1.179	13.09	1.309	11.31	1.131	1.21
1.8	12.26	1.226	13.57	1.357	11.75	1.175	1.25
1.9	12.78	1.278	14.17	1.417	12.43	1.243	1.31
5.1	22.5	2.25	23.78	2.378	21.84	2.184	2.27
7.1	25.98	2.598	27.24	2.724	25.09	2.509	2.61
8.7	27.31	2.731	28.42	2.842	26.5	2.65	2.74
12.1	31.2	3.12	33.01	3.301	29.15	2.915	3.11
13.1	33.4	3.34	35.51	3.551	31.29	3.129	3.34
14.1	34.47	3.447	36.41	3.641	32.15	3.215	3.43
14.9	35.02	3.502	36.96	3.696	32.7	3.27	3.49
15.7	35.52	3.552	37.46	3.746	33.2	3.32	3.54
18.7	37.32	3.732	38.96	3.896	34.55	3.455	3.69
19.3	37.77	3.777	39.41	3.941	35	3.5	3.74
19.9	38.22	3.822	39.86	3.986	35.45	3.545	3.78
20.5	38.67	3.867	40.31	4.031	35.9	3.59	3.83
21.1	39.12	3.912	40.76	4.076	36.35	3.635	3.87
21.6	39.47	3.947	41.11	4.111	36.7	3.67	3.91
22.2	39.82	3.982	41.46	4.146	37.05	3.705	3.94
22.7	40.17	4.017	41.81	4.181	37.4	3.74	3.98

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0	0	0	0	0	0	0.00
0.4	5.97	0.597	6.56	0.656	7.15	0.715	0.66
0.6	7.61	0.761	8.66	0.866	8.74	0.874	0.83
0.8	8.79	0.879	9.57	0.957	9.67	0.967	0.93
0.9	9.63	0.963	10.92	1.092	10.59	1.059	1.04
1.5	11.97	1.197	13.59	1.359	12.98	1.298	1.28
1.7	12.67	1.267	14.38	1.438	13.56	1.356	1.35
1.8	13.13	1.313	14.73	1.473	14.03	1.403	1.40
1.9	13.5	1.35	15.43	1.543	14.54	1.454	1.45
5.1	25.64	2.564	26.19	2.619	24.9	2.49	2.56
7.1	31.58	3.158	30.43	3.043	29.71	2.971	3.06
8.7	33.77	3.377	31.36	3.136	31.26	3.126	3.21
12.1	38.17	3.817	34.75	3.475	36.29	3.629	3.64
13.1	39.18	3.918	36.64	3.664	38.01	3.801	3.79
14.1	39.73	3.973	37.19	3.719	38.56	3.856	3.85
14.9	40.48	4.048	37.94	3.794	39.31	3.931	3.92
15.7	41.23	4.123	38.69	3.869	40.06	4.006	4.00
18.7	41.98	4.198	39.44	3.944	40.81	4.081	4.07
19.3	42.33	4.233	39.79	3.979	41.16	4.116	4.11
19.9	42.68	4.268	40.14	4.014	41.51	4.151	4.14
20.5	43.03	4.303	40.49	4.049	41.86	4.186	4.18
21.1	43.38	4.338	40.84	4.084	42.21	4.221	4.21
21.6	43.73	4.373	41.19	4.119	42.56	4.256	4.25
22.2	43.98	4.398	41.44	4.144	42.81	4.281	4.27
22.7	44.18	4.418	41.64	4.164	43.01	4.301	4.29

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F40 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	5.99	0.599	6.55	0.655	6.24	0.624	0.63
0.8	7.96	0.796	8.47	0.847	7.79	0.779	0.81
1.0	9.28	0.928	9.62	0.962	8.77	0.877	0.92
1.9	14.08	1.408	15.49	1.549	12.33	1.233	1.40
2.0	14.81	1.481	15.89	1.589	12.6	1.26	1.44
2.0	15.91	1.591	16.22	1.622	12.96	1.296	1.50
5.1	27.62	2.762	30.34	3.034	22.88	2.288	2.69
6.8	31.95	3.195	36.05	3.605	26.65	2.665	3.15
13.0	39.78	3.978	46.95	4.695	35.59	3.559	4.08
21.4	45.76	4.576	53.32	5.332	41.85	4.185	4.70
22.0	46.01	4.601	53.92	5.392	42.38	4.238	4.74
22.4	46.39	4.639	54.04	5.404	42.57	4.257	4.77

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – F60 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	11.36	1.136	9.8	0.98	11.03	1.103	1.07
0.8	15.47	1.547	12.95	1.295	14.04	1.404	1.42
1.0	18.83	1.883	15.15	1.515	15.85	1.585	1.66
1.9	29.08	2.908	24.5	2.45	23.35	2.335	2.56
2.0	30.39	3.039	25.29	2.529	23.85	2.385	2.65
2.0	31.47	3.147	26.21	2.621	24.41	2.441	2.74
5.1	52.69	5.269	47.48	4.748	42.35	4.235	4.75
6.8	61.27	6.127	55.6	5.56	49.34	4.934	5.54
13.0	79.30	7.93	75.97	7.597	66.21	6.621	7.38
21.4	91.40	9.14	91.93	9.193	77.66	7.766	8.70
22.0	92.05	9.205	92.7	9.27	78.31	7.831	8.77
22.4	92.39	9.239	92.9	9.29	78.46	7.846	8.79

SCC – F80 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.5	18.95	1.895	17.82	1.782	17.53	1.753	1.81
0.8	26.58	2.658	24.85	2.485	24.98	2.498	2.55
1.0	33.45	3.345	30.68	3.068	31.49	3.149	3.19
1.9	59.02	5.902	51.97	5.197	58.26	5.826	5.64
2.0	61.55	6.155	53.67	5.367	60.24	6.024	5.85
2.0	64.38	6.438	55.62	5.562	62.28	6.228	6.08
5.1	114.74	11.474	107.88	10.788	117.87	11.787	11.35
6.8	133.65	13.365	129.6	12.96	138.64	13.864	13.40
13.0	150.69	15.069	157.1	15.71	159.69	15.969	15.58
21.4	153.42	15.342	159.95	15.995	162.99	16.299	15.88
22.0	153.46	15.346	159.95	15.995	162.99	16.299	15.88
22.4	153.46	15.346	159.95	15.995	163.19	16.319	15.89

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – L10 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	9.44	0.944	7.63	0.763	7.09	0.709	0.81
0.8	12.33	1.233	10.65	1.065	9.12	0.912	1.07
0.9	14.61	1.461	12.14	1.214	10.72	1.072	1.25
1.8	24.01	2.401	18.6	1.86	17.84	1.784	2.02
1.9	25.36	2.536	19.68	1.968	18.41	1.841	2.12
2.0	26.71	2.671	20.34	2.034	19.06	1.906	2.20
5.1	53.07	5.307	41.47	4.147	42.47	4.247	4.57
6.8	64.69	6.469	50.15	5.015	51.62	5.162	5.55
13.0	89.85	8.985	68.05	6.805	70.81	7.081	7.62
21.4	103.43	10.343	82.08	8.208	85.36	8.536	9.03
22.0	103.99	10.399	82.89	8.289	87.47	8.747	9.15
22.4	105.36	10.536	83.66	8.366	88.11	8.811	9.24

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – L20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	0.59	0.059	2.42	0.242	2.55	0.255	0.25
1.7	2.18	0.218	10.7	1.07	9.44	0.944	1.01
2.0	2.39	0.239	12.9	1.29	11.65	1.165	1.23
5.2	6.45	0.645	34.18	3.418	30.23	3.023	3.22
7.1	8.08	0.808	43.09	4.309	37.19	3.719	4.01
8.6	9.09	0.909	48.67	4.867	40.29	4.029	4.45
10.0	10.11	1.011	52.38	5.238	42.02	4.202	4.72
11.1	11.34	1.134	55.25	5.525	43.83	4.383	4.95
12.1	11.79	1.179	57.04	5.704	44.54	4.454	5.08
14.1	11.99	1.199	59.5	5.95	46.05	4.605	5.28
14.9	13.31	1.331	61.31	6.131	48.29	4.829	5.48
15.7	13.71	1.371	62.21	6.221	48.88	4.888	5.55
16.5	14.15	1.415	63.47	6.347	49.55	4.955	5.65
18.4	15.38	1.538	65.26	6.526	50.9	5.09	5.81
20.7	15.99	1.599	66.73	6.673	51.63	5.163	5.92
24.5	17.64	1.764	69.85	6.985	53.92	5.392	6.19

SCC – L30 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	0.39	0.039	0.91	0.091	1.07	0.107	0.10
1.7	1.97	0.197	4.91	0.491	4.83	0.483	0.49
2.0	2.22	0.222	5.12	0.512	5.23	0.523	0.52
5.2	5.46	0.546	15.86	1.586	15.82	1.582	1.58
7.1	7.41	0.741	22.58	2.258	21.28	2.128	2.19
8.6	8.55	0.855	27.42	2.742	24.5	2.45	2.60
10.0	9.44	0.944	31.42	3.142	27.86	2.786	2.96
11.1	10.09	1.009	33.47	3.347	29.97	2.997	3.17
12.1	10.46	1.046	34.47	3.447	31.38	3.138	3.29
14.1	11.53	1.153	36.86	3.686	34.15	3.415	3.55
14.9	12.49	1.249	38.15	3.815	35.79	3.579	3.70
15.7	12.82	1.282	38.79	3.879	36.9	3.69	3.78
16.5	13.36	1.336	39.87	3.987	37.95	3.795	3.89
18.4	14.63	1.463	41.35	4.135	40.25	4.025	4.08
20.7	15.39	1.539	42.68	4.268	42.4	4.24	4.25
24.5	17.31	1.731	45.31	4.531	46.75	4.675	4.60

SCC – TB – G20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	1.08	0.108	1.6	0.16	1.89	0.189	0.13
1.7	7.27	0.727	9.31	0.931	8.77	0.877	0.83
2.0	8.54	0.854	11.42	1.142	9.95	0.995	1.00
5.2	25.72	2.572	30.85	3.085	28.29	2.829	2.83
7.1	35.53	3.553	39.48	3.948	38.55	3.855	3.75
8.6	40.46	4.046	44.17	4.417	46.31	4.631	4.23
10.0	44.22	4.422	47.94	4.794	53.27	5.327	4.61
11.1	46.17	4.617	50.3	5.03	58.43	5.843	4.82
12.1	47.51	4.751	51.96	5.196	62.17	6.217	4.97
14.1	50.29	5.029	54.92	5.492	69.94	6.994	5.26
14.9	52.00	5.2	56.44	5.644	72.99	7.299	5.42
15.7	53.00	5.3	57.17	5.717	75.1	7.51	5.51
16.5	54.10	5.41	58.13	5.813	76.98	7.698	5.61
18.4	56.13	5.613	59.84	5.984	80.65	8.065	5.80
20.7	57.51	5.751	61.17	6.117	83.13	8.313	5.93
24.5	60.15	6.015	63.45	6.345	87.28	8.728	6.18

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – G40 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	0.89	0.089	1.14	0.114	1.49	0.149	0.10
1.7	3.75	0.375	4.73	0.473	4.89	0.489	0.42
2.0	4.64	0.464	5.68	0.568	5.81	0.581	0.52
5.2	13.24	1.324	13.06	1.306	16.61	1.661	1.31
7.1	17.77	1.777	17.19	1.719	22.33	2.233	1.75
8.6	19.74	1.974	19.43	1.943	26.01	2.601	1.96
10.0	21.74	2.174	21.49	2.149	29.49	2.949	2.16
11.1	22.80	2.28	22.92	2.292	31.85	3.185	2.29
12.1	23.63	2.363	24	2.4	33.61	3.361	2.38
14.1	25.05	2.505	26.03	2.603	36.92	3.692	2.55
14.9	26.65	2.665	26.99	2.699	38.36	3.836	2.68
15.7	26.87	2.687	27.82	2.782	39.16	3.916	2.73
16.5	27.42	2.742	28.66	2.866	40.21	4.021	2.80
18.4	28.32	2.832	29.83	2.983	42.38	4.238	2.91
20.7	29.19	2.919	31.01	3.101	43.86	4.386	3.01
24.5	31.56	3.156	33.49	3.349	47.27	4.727	3.25

SCC – TB – G60 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	0.83	0.083	0.87	0.087	0.88	0.088	0.09
1.7	3.69	0.369	3.78	0.378	4.02	0.402	0.38
2.0	4.78	0.478	4.79	0.479	4.61	0.461	0.47
5.2	15.98	1.598	14.81	1.481	15.38	1.538	1.54
7.1	22.28	2.228	20.43	2.043	21.11	2.111	2.13
8.6	26.28	2.628	24.04	2.404	24.36	2.436	2.49
10.0	30.41	3.041	27.44	2.744	27.28	2.728	2.84
11.1	32.91	3.291	29.94	2.994	29.21	2.921	3.07
12.1	34.53	3.453	31.7	3.17	30.69	3.069	3.23
14.1	37.94	3.794	35.03	3.503	33.24	3.324	3.54
14.9	39.52	3.952	36.21	3.621	34.54	3.454	3.68
15.7	40.88	4.088	37.49	3.749	35.62	3.562	3.80
16.5	41.60	4.16	38.48	3.848	36.25	3.625	3.88
18.4	43.86	4.386	40.38	4.038	37.93	3.793	4.07
20.7	45.30	4.53	41.9	4.19	38.92	3.892	4.20
24.5	48.03	4.803	44.9	4.49	41.14	4.114	4.47

SCC – TB – G80 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	0.95	0.095	0.69	0.069	0.9	0.09	0.08
1.7	5.25	0.525	4.62	0.462	5.03	0.503	0.50
2.0	6.52	0.652	6.07	0.607	6.35	0.635	0.63
5.2	20.95	2.095	21.69	2.169	21.08	2.108	2.12
7.1	27.12	2.712	28.04	2.804	28.03	2.803	2.77
8.6	30.50	3.05	31.65	3.165	32.71	3.271	3.16
10.0	33.72	3.372	34.85	3.485	35.86	3.586	3.48
11.1	35.65	3.565	37.17	3.717	38.6	3.86	3.71
12.1	37.05	3.705	38.54	3.854	40.67	4.067	3.88
14.1	39.18	3.918	40.06	4.006	43.46	4.346	4.09
14.9	40.42	4.042	41.79	4.179	44.97	4.497	4.24
15.7	42.37	4.237	42.2	4.22	46.15	4.615	4.36
16.5	43.22	4.322	42.9	4.29	47.03	4.703	4.44
18.4	45.26	4.526	44.49	4.449	49.3	4.93	4.64
20.7	46.55	4.655	45.46	4.546	50.5	5.05	4.75
24.5	49.68	4.968	47.57	4.757	52.93	5.293	5.01

SCC – TB – F20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	1.10	0.11	0.82	0.082	1.79	0.179	0.12
1.7	7.26	0.726	9.7	0.97	11.33	1.133	0.94
2.0	8.24	0.824	11.09	1.109	12.67	1.267	1.07
5.2	23.55	2.355	26.99	2.699	29.14	2.914	2.66
7.1	32.02	3.202	33.69	3.369	36.52	3.652	3.41
8.6	37.34	3.734	37.83	3.783	40.52	4.052	3.86
10.0	41.51	4.151	40.58	4.058	43.18	4.318	4.18
11.1	44.28	4.428	42.43	4.243	44.85	4.485	4.39
12.1	46.02	4.602	43.3	4.33	45.8	4.58	4.50
14.1	48.56	4.856	45.2	4.52	47.36	4.736	4.70
14.9	49.95	4.995	46.56	4.656	48.26	4.826	4.83
15.7	50.33	5.033	47	4.7	48.72	4.872	4.87
16.5	51.23	5.123	47.46	4.746	49.43	4.943	4.94
18.4	52.40	5.24	48.41	4.841	50.39	5.039	5.04
20.7	53.14	5.314	48.98	4.898	50.72	5.072	5.09
24.5	53.97	5.397	49.74	4.974	51.68	5.168	5.18

SCC – TB – F40 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	0.48	0.048	0.87	0.087	1.13	0.113	0.08
1.7	8.38	0.838	9.46	0.946	9.99	0.999	0.93
2.0	9.47	0.947	11	1.1	11.03	1.103	1.05
5.2	22.92	2.292	25.05	2.505	25.59	2.559	2.45
7.1	30.45	3.045	32.98	3.298	33.5	3.35	3.23
8.6	35.42	3.542	38.1	3.81	38.31	3.831	3.73
10.0	39.22	3.922	41.61	4.161	42.41	4.241	4.11
11.1	42.20	4.22	44.87	4.487	45.86	4.586	4.43
12.1	44.23	4.423	46.75	4.675	47.98	4.798	4.63
14.1	48.13	4.813	50.17	5.017	52.21	5.221	5.02
14.9	50.34	5.034	53.01	5.301	54.2	5.42	5.25
15.7	52.04	5.204	53.26	5.326	55.56	5.556	5.36
16.5	53.48	5.348	54.29	5.429	56.96	5.696	5.49
18.4	56.58	5.658	56.85	5.685	59.73	5.973	5.77
20.7	58.70	5.87	58.28	5.828	61.76	6.176	5.96
24.5	61.82	6.182	60.55	6.055	65.23	6.523	6.25

Appendix 7 Tabulated Results – Sorptivity Raw Data – SCC

SCC – TB – F60 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	3.05	0.305	2.71	0.271	4.37	0.437	0.34
1.7	12.16	1.216	11.76	1.176	11.82	1.182	1.19
2.0	13.42	1.342	12.81	1.281	12.86	1.286	1.30
5.2	25.48	2.548	23.81	2.381	23.44	2.344	2.42
7.1	32.98	3.298	30.16	3.016	30.07	3.007	3.11
8.6	37.64	3.764	34.32	3.432	33.27	3.327	3.51
10.0	41.34	4.134	37.24	3.724	36.24	3.624	3.83
11.1	44.24	4.424	40.25	4.025	38.44	3.844	4.10
12.1	46.14	4.614	41.8	4.18	39.72	3.972	4.26
14.1	49.72	4.972	45.04	4.504	42.57	4.257	4.58
14.9	52.04	5.204	47.19	4.719	44.25	4.425	4.78
15.7	53.40	5.34	48.52	4.852	45.55	4.555	4.92
16.5	55.09	5.509	49.88	4.988	46.92	4.692	5.06
18.4	58.33	5.833	52.83	5.283	49.23	4.923	5.35
20.7	60.33	6.033	55.1	5.51	51.16	5.116	5.55
24.5	64.88	6.488	59.59	5.959	54.43	5.443	5.96

SCC – TB – F80 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0	0	0	0	0.00
0.4	9.02	0.902	10.16	1.016	12.8	1.28	1.07
1.7	33.86	3.386	37.98	3.798	39.28	3.928	3.70
2.0	38.13	3.813	43.08	4.308	44.21	4.421	4.18
5.2	84.87	8.487	95.63	9.563	91.53	9.153	9.07
7.1	113.03	11.303	126.16	12.616	118.91	11.891	11.94
8.6	128.34	12.834	143.73	14.373	132.06	13.206	13.47
10.0	133.91	13.391	149.97	14.997	136.95	13.695	14.03
11.1	136.91	13.691	153.06	15.306	139.48	13.948	14.32
12.1	137.09	13.709	153.31	15.331	139.83	13.983	14.34
14.1	137.29	13.729	153.61	15.361	140.21	14.021	14.37
14.9	138.54	13.854	155.1	15.51	141.91	14.191	14.52
15.7	139.04	13.904	155.58	15.558	142.52	14.252	14.57
16.5	139.59	13.959	155.86	15.586	142.77	14.277	14.61
18.4	140.53	14.053	156.91	15.691	143.44	14.344	14.70
20.7	140.53	14.053	157.27	15.727	144.19	14.419	14.73
24.5	140.53	14.053	157.49	15.749	144.19	14.419	14.74

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

Table A8-1 Sorptivity raw data for FC

FC – C (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.4	2.23	0.223	2.59	0.259	3.79	0.379	0.29
1.7	12.61	1.261	12.21	1.221	16.21	1.621	1.37
2.0	14.18	1.418	14.25	1.425	19.11	1.911	1.58
5.2	31.25	3.125	31.86	3.186	42.16	4.216	3.51
7.1	39.76	3.976	39.34	3.934	53.25	5.325	4.41
8.6	43.96	4.396	43.49	4.349	59.99	5.999	4.91
10.0	46.87	4.687	46.78	4.678	64.92	6.492	5.29
11.1	50.00	5	49.23	4.923	68.57	6.857	5.59
12.1	51.35	5.135	50.69	5.069	70.58	7.058	5.75
14.1	52.70	5.27	51.72	5.172	73.2	7.32	5.92
14.9	55.17	5.517	53.79	5.379	75.24	7.524	6.14
15.7	56.13	5.613	54.80	5.48	76.42	7.642	6.25
16.5	57.13	5.713	55.76	5.576	77.69	7.769	6.35
18.4	58.77	5.877	57.14	5.714	79.92	7.992	6.53
20.7	59.72	5.972	58.38	5.838	81.45	8.145	6.65
24.5	61.48	6.148	59.92	5.992	83.22	8.322	6.82

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – G40 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	13.10	1.31	11.46	1.146	12.95	1.295	1.25
1.6	16.59	1.659	15.30	1.53	16.19	1.619	1.60
1.9	18.34	1.834	16.77	1.677	18.34	1.834	1.78
8.5	64.68	6.468	56.65	5.665	67.91	6.791	6.31
9.8	70.60	7.06	60.58	6.058	74.62	7.462	6.86
12.0	79.90	7.99	66.53	6.653	85.69	8.569	7.74
16.2	91.90	9.19	72.82	7.282	97.86	9.786	8.75
20.8	98.93	9.893	77.24	7.724	101.49	10.149	9.26
21.4	100.18	10.018	79.73	7.973	103.73	10.373	9.45
21.9	101.34	10.134	80.99	8.099	105.43	10.543	9.59
22.4	102.30	10.23	81.95	8.195	106.39	10.639	9.69

FC – F20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	20.94	2.094	21.47	2.147	17.08	1.708	1.98
1.6	25.90	2.59	26.46	2.646	21.5	2.15	2.46
1.9	28.64	2.864	29.18	2.918	23.88	2.388	2.72
8.5	85.65	8.565	83.88	8.388	80.8	8.08	8.34
9.8	91.17	9.117	88.72	8.872	86.55	8.655	8.88
12.0	97.25	9.725	94.63	9.463	93.81	9.381	9.52
16.2	103.85	10.385	100.20	10.02	100.24	10.024	10.14
20.8	107.81	10.781	103.58	10.358	103.95	10.395	10.51
21.4	111.21	11.121	106.50	10.65	107.29	10.729	10.83
21.9	114.00	11.4	109.00	10.9	109.77	10.977	11.09
22.4	115.50	11.55	110.50	11.05	111.27	11.127	11.24

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – L20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	16.92	1.692	18.06	1.806	17	1.7	1.73
1.6	22.90	2.29	22.64	2.264	20.81	2.081	2.21
1.9	26.37	2.637	25.46	2.546	22.99	2.299	2.49
8.5	92.92	9.292	75.71	7.571	74.33	7.433	8.10
9.8	98.31	9.831	79.88	7.988	79.76	7.976	8.60
12.0	104.59	10.459	84.87	8.487	86.9	8.69	9.21
16.2	108.65	10.865	89.76	8.976	94.21	9.421	9.75
20.8	110.38	11.038	92.02	9.202	97.14	9.714	9.98
21.4	112.05	11.205	93.73	9.373	97.78	9.778	10.12
21.9	112.89	11.289	94.68	9.468	98.73	9.873	10.21
22.4	113.44	11.344	95.23	9.523	99.28	9.928	10.27

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – TB – G40 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	17.35	1.735	17.12	1.712	14.93	1.493	1.65
1.6	21.57	2.157	21.54	2.154	19.02	1.902	2.07
1.9	24.00	2.4	24.11	2.411	21.34	2.134	2.32
8.5	87.35	8.735	91.96	9.196	87.51	8.751	8.89
9.8	95.85	9.585	100.17	10.017	95.61	9.561	9.72
12.0	107.62	10.762	112.79	11.279	108.17	10.817	10.95
16.2	118.91	11.891	123.88	12.388	119.98	11.998	12.09
20.8	123.34	12.334	128.48	12.848	123.48	12.348	12.51
21.4	125.41	12.541	132.33	13.233	125.5	12.55	12.77
21.9	129.06	12.906	135.71	13.571	128.83	12.883	13.12
22.4	130.91	13.091	137.56	13.756	130.68	13.068	13.31

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – TB – F20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	17.66	1.766	24.42	2.442	19.27	1.927	2.05
1.6	22.00	2.2	29.78	2.978	23.91	2.391	2.52
1.9	24.56	2.456	33.20	3.32	26.72	2.672	2.82
8.5	81.99	8.199	98.99	9.899	82.7	8.27	8.79
9.8	87.22	8.722	103.44	10.344	86.5	8.65	9.24
12.0	93.11	9.311	108.49	10.849	92.13	9.213	9.79
16.2	99.65	9.965	113.14	11.314	98.17	9.817	10.37
20.8	103.75	10.375	114.87	11.487	101.09	10.109	10.66
21.4	104.89	10.489	116.50	11.65	102.21	10.221	10.79
21.9	106.03	10.603	117.92	11.792	103.41	10.341	10.91
22.4	106.68	10.668	118.57	11.857	104.06	10.406	10.98

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – C (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	11.02	1.102	10.70	1.07	11.02	1.102	1.09
1.7	14.38	1.438	13.82	1.382	14.04	1.404	1.39
1.9	16.64	1.664	15.95	1.595	15.79	1.579	1.59
8.5	70.37	7.037	39.20	3.92	36.76	3.676	3.80
9.8	77.61	7.761	39.99	3.999	37.36	3.736	3.87
12.0	87.74	8.774	40.88	4.088	38.61	3.861	3.97
16.2	94.56	9.456	42.35	4.235	39.51	3.951	4.09
20.8	96.23	9.623	43.36	4.336	40.95	4.095	4.22
21.4	96.35	9.635	44.07	4.407	41.57	4.157	4.28

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – G40 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	9.39	0.939	9.67	0.967	10.01	1.001	0.95
1.7	11.91	1.191	12.21	1.221	12.36	1.236	1.21
1.9	13.29	1.329	14.00	1.4	14.05	1.405	1.36
8.5	34.67	3.467	47.40	4.74	62	6.2	4.10
9.8	35.90	3.59	50.30	5.03	70.8	7.08	4.31
12.0	36.82	3.682	53.28	5.328	84.35	8.435	4.51
16.2	40.12	4.012	55.22	5.522	98.43	9.843	4.77
20.8	42.75	4.275	57.11	5.711	101.99	10.199	4.99
21.4	42.82	4.282	57.20	5.72	102.87	10.287	5.00

FC – F20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	12.68	1.268	12.53	1.253	13.34	1.334	1.28
1.7	15.84	1.584	15.63	1.563	16.36	1.636	1.59
1.9	18.22	1.822	18.19	1.819	18.48	1.848	1.83
8.5	70.77	7.077	74.69	7.469	58.93	5.893	6.81
9.8	77.58	7.758	81.58	8.158	62.9	6.29	7.40
12.0	86.65	8.665	90.73	9.073	68.24	6.824	8.19
16.2	94.47	9.447	97.10	9.71	73.79	7.379	8.85
20.8	96.60	9.66	99.06	9.906	77.61	7.761	9.11
21.4	96.80	9.68	99.55	9.955	77.74	7.774	9.14
21.9	96.80	9.68	99.55	9.955	77.79	7.779	9.14
22.4	96.80	9.68	99.55	9.955	77.79	7.779	9.14

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – L20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	12.36	1.236	9.47	0.947	15.57	1.557	1.25
1.7	16.12	1.612	13.10	1.31	19.89	1.989	1.64
1.9	19.27	1.927	16.15	1.615	23.26	2.326	1.96
8.5	60.81	6.081	58.34	5.834	74.69	7.469	6.46
9.8	70.42	7.042	67.75	6.775	83	8.3	7.37
12.0	79.65	7.965	77.16	7.716	89.21	8.921	8.20
16.2	84.45	8.445	81.59	8.159	91.22	9.122	8.58
20.8	84.80	8.48	82.03	8.203	91.7	9.17	8.62
21.4	85.30	8.53	82.53	8.253	92.2	9.22	8.67
21.9	85.80	8.58	83.03	8.303	92.7	9.27	8.72
22.4	86.30	8.63	83.53	8.353	93.2	9.32	8.77

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – TB – G40 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	12.46	1.246	10.38	1.038	17.57	1.757	1.40
1.7	15.39	1.539	12.66	1.266	19.53	1.953	1.61
1.9	17.07	1.707	14.51	1.451	20.88	2.088	1.77
8.5	73.67	7.367	63.78	6.378	61.83	6.183	6.28
9.8	82.77	8.277	71.10	7.11	66.32	6.632	6.87
12.0	96.92	9.692	80.91	8.091	72.29	7.229	7.66
16.2	111.55	11.155	89.59	8.959	77.75	7.775	8.37
20.8	116.21	11.621	93.64	9.364	80.9	8.09	8.73
21.4	116.31	11.631	93.66	9.366	80.92	8.092	8.73
21.9	116.67	11.667	93.82	9.382	80.94	8.094	8.74
22.4	116.67	11.667	93.82	9.382	80.94	8.094	8.74

FC – TB – F20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	17.58	1.758	15.71	1.571	13.65	1.365	1.47
1.7	22.54	2.254	19.64	1.964	16.66	1.666	1.82
1.9	25.69	2.569	22.06	2.206	18.63	1.863	2.03
8.5	97.22	9.722	67.47	6.747	69.23	6.923	6.84
9.8	106.57	10.657	71.70	7.17	74.34	7.434	7.30
12.0	117.91	11.791	76.92	7.692	80.92	8.092	7.89
16.2	125.04	12.504	83.05	8.305	87.27	8.727	8.52
20.8	125.59	12.559	87.11	8.711	91.09	9.109	8.91
21.4	125.71	12.571	87.24	8.724	91.16	9.116	8.92
21.9	126.01	12.601	87.54	8.754	91.46	9.146	8.95
22.4	126.31	12.631	87.84	8.784	91.76	9.176	8.98

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – C (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.3	3.01	0.301	3.46	0.346	3.29	0.329	0.33
0.5	6.01	0.601	6.01	0.601	5.68	0.568	0.59
0.7	6.89	0.689	7.11	0.711	6.66	0.666	0.69
1.4	8.91	0.891	10.49	1.049	9.6	0.96	0.97
1.6	9.70	0.97	11.80	1.18	10.76	1.076	1.08
1.9	10.15	1.015	12.74	1.274	11.77	1.177	1.16
4.8	12.04	1.204	15.66	1.566	16.78	1.678	1.48
7.1	13.01	1.301	17.52	1.752	18.64	1.864	1.64
8.5	13.47	1.347	18.04	1.804	19.38	1.938	1.70
9.9	13.96	1.396	18.55	1.855	19.98	1.998	1.75
12.4	14.72	1.472	19.35	1.935	21.02	2.102	1.84
13.2	15.14	1.514	19.65	1.965	21.26	2.126	1.87
13.9	15.61	1.561	20.15	2.015	21.87	2.187	1.92
14.8	15.94	1.594	20.73	2.073	22.27	2.227	1.96
15.5	16.02	1.602	20.78	2.078	22.42	2.242	1.97
16.3	16.25	1.625	21.14	2.114	22.63	2.263	2.00
18.3	17.44	1.744	22.35	2.235	23.79	2.379	2.12
19.1	17.71	1.771	22.72	2.272	23.99	2.399	2.15
19.6	17.80	1.78	22.83	2.283	24.17	2.417	2.16
20.2	17.99	1.799	23.07	2.307	24.53	2.453	2.19
20.8	18.60	1.86	23.39	2.339	24.8	2.48	2.23
22.0	18.75	1.875	23.86	2.386	25.32	2.532	2.26
22.4	19.46	1.946	24.42	2.442	25.64	2.564	2.32

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – G40 (91 days)

Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.3	2.12	0.212	2.23	0.223	5.7	0.57	0.22
0.5	4.45	0.445	3.96	0.396	6.84	0.684	0.42
0.7	5.34	0.534	5.06	0.506	7.66	0.766	0.52
1.4	8.37	0.837	7.45	0.745	11.36	1.136	0.79
1.6	9.35	0.935	8.47	0.847	12.53	1.253	0.89
1.9	10.51	1.051	10.27	1.027	14.32	1.432	1.04
4.8	17.33	1.733	20.01	2.001	28.62	2.862	1.87
7.1	19.29	1.929	24.38	2.438	36.35	3.635	2.18
8.5	19.76	1.976	25.96	2.596	39.22	3.922	2.29
9.9	20.38	2.038	27.02	2.702	41.59	4.159	2.37
12.4	21.23	2.123	28.23	2.823	44.34	4.434	2.47
13.2	21.52	2.152	28.64	2.864	45.33	4.533	2.51
13.9	22.11	2.211	29.39	2.939	46.16	4.616	2.57
14.8	22.37	2.237	29.68	2.968	47.11	4.711	2.60
15.5	22.53	2.253	29.81	2.981	47.48	4.748	2.62
16.3	22.64	2.264	30.07	3.007	47.93	4.793	2.64
18.3	23.57	2.357	31.13	3.113	49.85	4.985	2.73
19.1	23.88	2.388	31.52	3.152	50.31	5.031	2.77
19.6	24.03	2.403	31.58	3.158	50.73	5.073	2.78
20.2	24.18	2.418	31.96	3.196	51.03	5.103	2.81
20.8	24.55	2.455	32.10	3.21	51.54	5.154	2.83
22.0	24.88	2.488	32.55	3.255	51.93	5.193	2.87
22.4	25.56	2.556	33.44	3.344	52.7	5.27	2.95

FC – F20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.3	3.67	0.367	5.24	0.524	3.1	0.31	0.40
0.5	7.08	0.708	7.66	0.766	6.52	0.652	0.71
0.7	8.38	0.838	8.46	0.846	7.55	0.755	0.81
1.4	13.19	1.319	12.26	1.226	10.97	1.097	1.21
1.6	14.45	1.445	13.63	1.363	11.56	1.156	1.32
1.9	16.32	1.632	14.83	1.483	12.54	1.254	1.46
4.8	28.34	2.834	22.76	2.276	16.83	1.683	2.26
7.1	32.38	3.238	25.35	2.535	18.41	1.841	2.54
8.5	33.70	3.37	26.50	2.65	18.98	1.898	2.64
9.9	34.94	3.494	27.35	2.735	19.41	1.941	2.72
12.4	37.24	3.724	28.93	2.893	20.12	2.012	2.88
13.2	38.01	3.801	29.36	2.936	20.73	2.073	2.94
13.9	38.63	3.863	29.47	2.947	20.77	2.077	2.96
14.8	39.10	3.91	29.92	2.992	21.09	2.109	3.00
15.5	39.36	3.936	30.07	3.007	21.21	2.121	3.02
16.3	39.52	3.952	30.48	3.048	21.39	2.139	3.05
18.3	40.94	4.094	31.59	3.159	22.37	2.237	3.16
19.1	41.46	4.146	32.22	3.222	22.91	2.291	3.22
19.6	41.69	4.169	32.31	3.231	23.05	2.305	3.24
20.2	41.81	4.181	32.79	3.279	23.16	2.316	3.26
20.8	42.58	4.258	32.97	3.297	23.53	2.353	3.30
22.0	43.33	4.333	33.76	3.376	24.03	2.403	3.37
22.4	43.71	4.371	34.23	3.423	24.29	2.429	3.41

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – L20 (91 days)

Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.3	2.60	0.26	2.48	0.248	3.42	0.342	0.28
0.5	4.73	0.473	4.55	0.455	5.58	0.558	0.50
0.7	5.89	0.589	5.83	0.583	6.83	0.683	0.62
1.4	8.53	0.853	8.61	0.861	11.32	1.132	0.95
1.6	9.46	0.946	9.58	0.958	12.83	1.283	1.06
1.9	10.26	1.026	10.15	1.015	14.36	1.436	1.16
4.8	15.25	1.525	13.20	1.32	23.13	2.313	1.72
7.1	16.90	1.69	14.61	1.461	26.31	2.631	1.93
8.5	17.79	1.779	15.49	1.549	27.54	2.754	2.03
9.9	18.47	1.847	16.23	1.623	28.57	2.857	2.11
12.4	19.55	1.955	17.43	1.743	30.14	3.014	2.24
13.2	19.90	1.99	17.84	1.784	30.72	3.072	2.28
13.9	20.57	2.057	18.51	1.851	31.28	3.128	2.35
14.8	20.91	2.091	18.80	1.88	31.71	3.171	2.38
15.5	21.13	2.113	19.04	1.904	32.12	3.212	2.41
16.3	21.32	2.132	19.49	1.949	32.39	3.239	2.44
18.3	22.78	2.278	20.90	2.09	33.85	3.385	2.58
19.1	23.12	2.312	21.28	2.128	34.37	3.437	2.63
19.6	23.29	2.329	21.38	2.138	34.81	3.481	2.65
20.2	23.51	2.351	21.74	2.174	34.9	3.49	2.67
20.8	24.13	2.413	22.05	2.205	35.28	3.528	2.72
22.0	24.44	2.444	22.58	2.258	36.01	3.601	2.77
22.4	24.90	2.49	23.16	2.316	36.42	3.642	2.82

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

FC – TB – G40 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.3	3.94	0.394	6.58	0.658	3.17	0.317	0.46
0.5	5.38	0.538	7.97	0.797	5.01	0.501	0.61
0.7	6.22	0.622	8.86	0.886	6	0.6	0.70
1.4	9.71	0.971	12.66	1.266	10.04	1.004	1.08
1.6	10.88	1.088	13.86	1.386	11.26	1.126	1.20
1.9	12.54	1.254	15.57	1.557	13.2	1.32	1.38
4.8	31.30	3.13	35.21	3.521	33.36	3.336	3.33
7.1	47.07	4.707	51.91	5.191	49.93	4.993	4.96
8.5	55.43	5.543	60.52	6.052	58.33	5.833	5.81
9.9	63.61	6.361	68.93	6.893	66.29	6.629	6.63
12.4	75.32	7.532	81.10	8.11	77.36	7.736	7.79
13.2	78.83	7.883	84.42	8.442	80.45	8.045	8.12
13.9	81.24	8.124	86.95	8.695	82.67	8.267	8.36
14.8	84.23	8.423	90.10	9.01	85.51	8.551	8.66
15.5	86.07	8.607	91.93	9.193	87.23	8.723	8.84
16.3	87.92	8.792	93.97	9.397	89.08	8.908	9.03
18.3	91.95	9.195	98.23	9.823	92.98	9.298	9.44
19.1	93.31	9.331	100.03	10.003	94.31	9.431	9.59
19.6	94.03	9.403	100.71	10.071	94.99	9.499	9.66
20.2	94.83	9.483	101.32	10.132	95.63	9.563	9.73
20.8	95.79	9.579	102.42	10.242	96.63	9.663	9.83
22.0	97.12	9.712	103.83	10.383	97.71	9.771	9.96
22.4	97.88	9.788	104.58	10.458	98.39	9.839	10.03

FC – TB – F20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.3	3.51	0.351	4.31	0.431	4.28	0.428	0.40
0.5	5.40	0.54	6.63	0.663	6.43	0.643	0.62
0.7	6.46	0.646	8.04	0.804	7.81	0.781	0.74
1.4	10.96	1.096	13.41	1.341	13.01	1.301	1.25
1.6	12.00	1.2	14.88	1.488	14.75	1.475	1.39
1.9	13.70	1.37	17.17	1.717	16.54	1.654	1.58
4.8	24.95	2.495	32.94	3.294	30.27	3.027	2.94
7.1	30.05	3.005	40.15	4.015	36.22	3.622	3.55
8.5	32.28	3.228	43.31	4.331	38.68	3.868	3.81
9.9	33.96	3.396	45.71	4.571	40.86	4.086	4.02
12.4	36.57	3.657	49.34	4.934	43.92	4.392	4.33
13.2	37.42	3.742	50.11	5.011	44.89	4.489	4.41
13.9	38.07	3.807	51.20	5.12	45.7	4.57	4.50
14.8	38.97	3.897	52.26	5.226	46.59	4.659	4.59
15.5	39.23	3.923	52.68	5.268	47.17	4.717	4.64
16.3	40.16	4.016	53.54	5.354	47.79	4.779	4.72
18.3	42.02	4.202	55.65	5.565	49.69	4.969	4.91
19.1	42.67	4.267	56.34	5.634	50.65	5.065	4.99
19.6	43.19	4.319	56.71	5.671	51.11	5.111	5.03
20.2	43.65	4.365	57.15	5.715	51.23	5.123	5.07
20.8	44.46	4.446	57.68	5.768	51.98	5.198	5.14
22.0	45.37	4.537	58.70	5.87	52.81	5.281	5.23
22.4	45.77	4.577	59.10	5.91	53.42	5.342	5.28

Table A8-2 Sorptivity raw data for UWC

UWC – C (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	14.70	1.47	15.15	1.515	17.24	1.724	1.57
1.6	18.76	1.876	18.87	1.887	21.02	2.102	1.95
1.9	21.47	2.147	20.54	2.054	23.12	2.312	2.17
8.5	66.21	6.621	67.09	6.709	71.85	7.185	6.84
9.8	70.79	7.079	71.73	7.173	77.39	7.739	7.33
12.0	76.06	7.606	76.99	7.699	81.36	8.136	7.81
16.2	81.31	8.131	81.89	8.189	86.33	8.633	8.32
20.8	83.56	8.356	82.27	8.227	86.55	8.655	8.41
21.4	83.59	8.359	82.68	8.268	86.95	8.695	8.44
21.9	83.84	8.384	82.93	8.293	87.2	8.72	8.47
22.4	84.09	8.409	83.18	8.318	87.45	8.745	8.49

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

UWC – G40 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	14.81	1.481	15.37	1.537	13.24	1.324	1.45
1.6	18.50	1.85	19.15	1.915	16.6	1.66	1.81
1.9	20.99	2.099	21.23	2.123	18.35	1.835	2.02
8.5	80.38	8.038	83.85	8.385	69.84	6.984	7.80
9.8	88.13	8.813	91.96	9.196	77.2	7.72	8.58
12.0	98.53	9.853	102.49	10.249	87.91	8.791	9.63
16.2	106.97	10.697	109.21	10.921	97.64	9.764	10.46
20.8	108.15	10.815	109.65	10.965	99.86	9.986	10.59
21.4	108.40	10.84	109.90	10.99	100.11	10.011	10.61
21.9	108.65	10.865	110.15	11.015	100.36	10.036	10.64
22.4	108.90	10.89	110.40	11.04	100.61	10.061	10.66

UWC – F20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	11.84	1.184	12.10	1.21	11.21	1.121	1.17
1.6	15.18	1.518	15.13	1.513	14.5	1.45	1.49
1.9	17.14	1.714	17.03	1.703	16.69	1.669	1.70
8.5	62.61	6.261	55.75	5.575	67.11	6.711	6.18
9.8	66.44	6.644	59.40	5.94	73.08	7.308	6.63
12.0	71.81	7.181	63.95	6.395	79.89	7.989	7.19
16.2	76.61	7.661	68.39	6.839	86.41	8.641	7.71
20.8	80.19	8.019	70.37	7.037	89.71	8.971	8.01
21.4	80.78	8.078	70.80	7.08	90.04	9.004	8.05
21.9	81.06	8.106	71.45	7.145	90.51	9.051	8.10
22.4	81.41	8.141	71.80	7.18	90.86	9.086	8.14

UWC – L20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	13.54	1.354	16.31	1.631	12.09	1.209	1.40
1.6	19.13	1.913	21.63	2.163	16.84	1.684	1.92
1.9	21.85	2.185	24.27	2.427	19.52	1.952	2.19
8.5	80.54	8.054	88.73	8.873	76.4	7.64	8.19
9.8	86.41	8.641	95.75	9.575	81.5	8.15	8.79
12.0	93.46	9.346	104.32	10.432	86.99	8.699	9.49
16.2	99.78	9.978	109.79	10.979	92.78	9.278	10.08
20.8	101.68	10.168	112.12	11.212	95.38	9.538	10.31
21.4	101.74	10.174	112.28	11.228	95.6	9.56	10.32
21.9	101.94	10.194	112.48	11.248	95.8	9.58	10.34
22.4	102.14	10.214	112.68	11.268	96	9.6	10.36

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

UWC – TB – G40 (7 days)

Sample	A		B		C		Average Water intake/unit area (Kg/m^2)
Time (h$^{0.5}$)	Water intake (g)	Water intake/unit area (Kg/m^2)	Water intake (g)	Water intake/unit area (Kg/m^2)	Water intake (g)	Water intake/unit area (Kg/m^2)	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	15.70	1.57	16.05	1.605	14.98	1.498	1.56
1.6	19.81	1.981	20.17	2.017	19.29	1.929	1.98
1.9	22.51	2.251	23.62	2.362	21.85	2.185	2.27
8.5	87.15	8.715	87.78	8.778	88.99	8.899	8.80
9.8	95.88	9.588	96.44	9.644	99.8	9.98	9.74
12.0	107.61	10.761	107.88	10.788	112.19	11.219	10.92
16.2	115.46	11.546	116.53	11.653	119.79	11.979	11.73
20.8	120.46	12.046	121.53	12.153	124.79	12.479	12.23
21.4	121.56	12.156	122.63	12.263	125.89	12.589	12.34
21.9	122.20	12.22	123.27	12.327	126.53	12.653	12.40
22.4	122.52	12.252	123.59	12.359	126.85	12.685	12.43

UWC – TB – F20 (7 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.3	25.70	2.57	16.14	1.614	18.92	1.892	2.03
1.6	31.40	3.14	22.33	2.233	23.11	2.311	2.56
1.9	35.42	3.542	26.04	2.604	25.54	2.554	2.90
8.5	108.05	10.805	95.87	9.587	68.68	6.868	9.09
9.8	115.79	11.579	103.68	10.368	72.66	7.266	9.74
12.0	124.61	12.461	113.95	11.395	77.92	7.792	10.55
16.2	129.86	12.986	121.37	12.137	83.38	8.338	11.15
20.8	132.07	13.207	123.48	12.348	86.96	8.696	11.42
21.4	132.82	13.282	124.23	12.423	87.71	8.771	11.49
21.9	133.22	13.322	124.63	12.463	88.11	8.811	11.53
22.4	133.46	13.346	124.87	12.487	88.35	8.835	11.56

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

UWC – C (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.4	11.96	1.196	12.61	1.261	12.33	1.233	1.23
1.7	14.54	1.454	15.68	1.568	15.67	1.567	1.53
1.9	16.12	1.612	17.74	1.774	17.83	1.783	1.72
8.5	35.43	3.543	66.06	6.606	71.45	7.145	5.76
9.8	36.14	3.614	67.62	6.762	74.64	7.464	5.95
12.0	37.40	3.74	69.10	6.91	77.91	7.791	6.15
16.2	39.31	3.931	70.76	7.076	79.84	7.984	6.33
20.8	41.25	4.125	72.14	7.214	82.27	8.227	6.52
21.4	41.57	4.157	72.51	7.251	82.71	8.271	6.56
21.9	41.81	4.181	72.75	7.275	82.95	8.295	6.58
22.4	42.05	4.205	72.99	7.299	83.19	8.319	6.61

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

UWC – G40 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.4	11.93	1.193	12.62	1.262	11.79	1.179	1.23
1.7	14.64	1.464	15.24	1.524	14.77	1.477	1.49
1.9	16.43	1.643	17.06	1.706	16.38	1.638	1.67
8.5	55.30	5.53	51.08	5.108	82.84	8.284	5.32
9.8	57.25	5.725	53.60	5.36	93.28	9.328	5.54
12.0	59.03	5.903	54.45	5.445	102.72	10.272	5.67
16.2	60.78	6.078	55.67	5.567	109.17	10.917	5.82
20.8	62.25	6.225	56.59	5.659	111.8	11.18	5.94
21.4	62.38	6.238	56.73	5.673	112.2	11.22	5.96
21.9	62.54	6.254	56.80	5.68	112.38	11.238	5.97
22.4	62.66	6.266	56.92	5.692	112.5	11.25	5.98

UWC – F20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.4	11.70	1.17	11.93	1.193	14.76	1.476	1.18
1.7	14.03	1.403	14.68	1.468	17.82	1.782	1.44
1.9	15.23	1.523	16.26	1.626	19.69	1.969	1.57
8.5	39.05	3.905	65.17	6.517	77.01	7.701	5.21
9.8	40.61	4.061	70.77	7.077	84.6	8.46	5.57
12.0	42.84	4.284	76.45	7.645	94.57	9.457	5.96
16.2	45.09	4.509	81.46	8.146	103.55	10.355	6.33
20.8	47.84	4.784	85.26	8.526	108.7	10.87	6.65
21.4	48.24	4.824	85.66	8.566	109.1	10.91	6.70
21.9	48.64	4.864	86.06	8.606	109.5	10.95	6.74
22.4	49.04	4.904	86.46	8.646	109.9	10.99	6.78

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

UWC – L20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
1.4	13.04	1.304	11.00	1.1	10.24	1.024	1.14
1.7	16.25	1.625	13.19	1.319	13.07	1.307	1.42
1.9	18.73	1.873	14.54	1.454	14.72	1.472	1.60
8.5	60.73	6.073	28.99	2.899	57.95	5.795	4.92
9.8	61.30	6.13	29.89	2.989	61.03	6.103	5.07
12.0	62.50	6.25	30.84	3.084	63.19	6.319	5.22
16.2	65.14	6.514	32.44	3.244	64.09	6.409	5.39
20.8	67.35	6.735	33.97	3.397	65.33	6.533	5.56
21.4	67.57	6.757	34.24	3.424	65.76	6.576	5.59
21.9	67.83	6.783	34.49	3.449	65.99	6.599	5.61
22.4	67.98	6.798	34.64	3.464	66.14	6.614	5.63

UWC – TB – G40 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.3	3.32	0.332	4.95	0.495	3.04	0.304	0.38
0.5	5.91	0.591	7.46	0.746	5.61	0.561	0.63
0.7	7.38	0.738	8.50	0.85	6.58	0.658	0.75
1.4	11.93	1.193	12.58	1.258	10.5	1.05	1.17
1.6	13.66	1.366	13.86	1.386	12.07	1.207	1.32
1.9	15.26	1.526	15.43	1.543	13.94	1.394	1.49
4.8	36.33	3.633	35.21	3.521	35.32	3.532	3.56
7.1	52.23	5.223	52.20	5.22	51.12	5.112	5.19
8.5	59.66	5.966	60.65	6.065	57.47	5.747	5.93
9.9	66.32	6.632	67.84	6.784	62.24	6.224	6.55
12.4	74.37	7.437	75.47	7.547	66.98	6.698	7.23
13.2	76.46	7.646	77.27	7.727	67.93	6.793	7.39
13.9	78.93	7.893	79.20	7.92	69.26	6.926	7.58
14.8	81.10	8.11	80.64	8.064	69.83	6.983	7.72
15.5	82.35	8.235	81.58	8.158	70.29	7.029	7.81
16.3	83.83	8.383	82.39	8.239	70.7	7.07	7.90
18.3	89.22	8.922	85.19	8.519	72.45	7.245	8.23
19.1	90.96	9.096	85.97	8.597	72.86	7.286	8.33
19.6	91.67	9.167	86.24	8.624	72.94	7.294	8.36
20.2	92.70	9.27	86.60	8.66	73.32	7.332	8.42
20.8	94.01	9.401	87.21	8.721	73.81	7.381	8.50
22.0	95.46	9.546	88.24	8.824	74.31	7.431	8.60
22.4	95.86	9.586	88.29	8.829	74.82	7.482	8.63

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

UWC – TB – F20 (28 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.3	7.08	0.708	4.10	0.41	4.34	0.434	0.42
0.5	9.09	0.909	5.56	0.556	6.08	0.608	0.58
0.7	10.47	1.047	6.38	0.638	7.42	0.742	0.69
1.4	17.57	1.757	10.53	1.053	12.17	1.217	1.13
1.6	19.72	1.972	11.42	1.142	13.74	1.374	1.26
1.9	23.14	2.314	12.85	1.285	15.72	1.572	1.43
4.8	56.29	5.629	23.16	2.316	35.42	3.542	2.93
7.1	79.27	7.927	28.89	2.889	45.58	4.558	3.72
8.5	90.38	9.038	31.07	3.107	50.06	5.006	4.06
9.9	100.97	10.097	33.00	3.3	54.08	5.408	4.35
12.4	117.21	11.721	36.02	3.602	60.4	6.04	4.82
13.2	121.94	12.194	37.27	3.727	62.55	6.255	4.99
13.9	125.66	12.566	37.89	3.789	64.12	6.412	5.10
14.8	129.94	12.994	38.75	3.875	66.17	6.617	5.25
15.5	132.17	13.217	39.29	3.929	67.53	6.753	5.34
16.3	135.03	13.503	40.09	4.009	69.21	6.921	5.46
18.3	140.21	14.021	42.06	4.206	73.15	7.315	5.76
19.1	141.02	14.102	42.41	4.241	74.3	7.43	5.84
19.6	141.26	14.126	42.82	4.282	75.06	7.506	5.89
20.2	142.25	14.225	43.29	4.329	76.21	7.621	5.97
20.8	143.49	14.349	44.04	4.404	77.55	7.755	6.08
22.0	144.50	14.45	44.85	4.485	79.23	7.923	6.20
22.4	145.10	14.51	45.11	4.511	79.87	7.987	6.25

Appendix 8 Tabulated Results – Sorptivity Raw Data – FC and UWC

UWC – C (91 days)

Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.4	2.66	0.266	2.82	0.282	4.49	0.449	0.36
0.6	4.06	0.406	4.26	0.426	5.55	0.555	0.48
0.7	4.78	0.478	4.90	0.49	6.2	0.62	0.55
1.4	6.45	0.645	9.23	0.923	7.05	0.705	0.68
1.6	7.07	0.707	10.16	1.016	7.31	0.731	0.72
1.9	7.34	0.734	11.95	1.195	7.44	0.744	0.74
4.8	9.80	0.98	28.57	2.857	8.55	0.855	0.92
7.1	10.37	1.037	41.89	4.189	8.91	0.891	0.96
8.5	10.81	1.081	49.29	4.929	9.12	0.912	1.00
9.9	11.40	1.14	56.81	5.681	9.33	0.933	1.04
12.4	12.09	1.209	68.49	6.849	9.92	0.992	1.10
13.2	12.16	1.216	72.14	7.214	9.96	0.996	1.11
13.9	12.45	1.245	74.70	7.47	10.24	1.024	1.13
14.8	12.72	1.272	78.63	7.863	10.56	1.056	1.16
15.5	12.92	1.292	80.84	8.084	10.61	1.061	1.18
16.3	13.12	1.312	83.64	8.364	10.74	1.074	1.19
18.3	13.47	1.347	89.78	8.978	11.47	1.147	1.25
19.1	13.91	1.391	92.10	9.21	11.86	1.186	1.29
19.6	14.13	1.413	93.79	9.379	12.08	1.208	1.31
20.2	14.19	1.419	94.79	9.479	12.28	1.228	1.32
20.8	14.59	1.459	96.37	9.637	12.49	1.249	1.35
22.0	14.99	1.499	98.77	9.877	12.78	1.278	1.39
22.5	15.34	1.534	99.49	9.949	12.99	1.299	1.42

UWC – G40 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.4	3.54	0.354	4.19	0.419	4.94	0.494	0.39
0.6	5.07	0.507	5.69	0.569	6.05	0.605	0.54
0.7	6.03	0.603	6.60	0.66	6.78	0.678	0.63
1.4	9.50	0.95	10.46	1.046	10.31	1.031	1.00
1.6	10.69	1.069	11.65	1.165	11.55	1.155	1.12
1.9	12.31	1.231	13.41	1.341	13.43	1.343	1.29
4.8	23.59	2.359	26.84	2.684	40.81	4.081	2.52
7.1	28.21	2.821	31.31	3.131	68.39	6.839	2.98
8.5	29.22	2.922	32.45	3.245	83.86	8.386	3.08
9.9	30.50	3.05	33.53	3.353	99.82	9.982	3.20
12.4	31.74	3.174	34.76	3.476	124.69	12.469	3.32
13.2	32.22	3.222	35.37	3.537	131.98	13.198	3.38
13.9	32.51	3.251	35.72	3.572	137.81	13.781	3.41
14.8	32.84	3.284	36.18	3.618	144.41	14.441	3.45
15.5	33.06	3.306	36.43	3.643	148.11	14.811	3.47
16.3	33.23	3.323	36.68	3.668	151.31	15.131	3.50
18.3	34.28	3.428	37.54	3.754	155.95	15.595	3.59
19.1	34.35	3.435	37.66	3.766	156.63	15.663	3.60
19.6	34.43	3.443	37.74	3.774	157.03	15.703	3.61
20.2	34.63	3.463	38.00	3.8	157.41	15.741	3.63
20.8	35.19	3.519	38.39	3.839	157.93	15.793	3.68
22.0	35.81	3.581	39.23	3.923	158.7	15.87	3.75
22.5	35.96	3.596	39.30	3.93	159.14	15.914	3.76

UWC – F20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time (h$^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.4	3.60	0.36	3.51	0.351	4	0.4	0.37
0.6	5.07	0.507	4.72	0.472	5.68	0.568	0.52
0.7	5.95	0.595	5.29	0.529	6.3	0.63	0.58
1.4	10.24	1.024	7.90	0.79	10.25	1.025	0.95
1.6	11.56	1.156	8.82	0.882	11.62	1.162	1.07
1.9	13.66	1.366	9.50	0.95	13.02	1.302	1.21
4.8	35.65	3.565	14.25	1.425	33.51	3.351	2.78
7.1	52.28	5.228	16.25	1.625	48.9	4.89	3.91
8.5	60.54	6.054	17.10	1.71	56.41	5.641	4.47
9.9	68.41	6.841	17.82	1.782	63.36	6.336	4.99
12.4	80.67	8.067	18.84	1.884	72.46	7.246	5.73
13.2	84.58	8.458	19.38	1.938	74.8	7.48	5.96
13.9	87.34	8.734	20.04	2.004	76.47	7.647	6.13
14.8	90.69	9.069	20.42	2.042	78.3	7.83	6.31
15.5	92.89	9.289	20.62	2.062	79.4	7.94	6.43
16.3	95.52	9.552	20.87	2.087	80.69	8.069	6.57
18.3	101.19	10.119	22.02	2.202	83.4	8.34	6.89
19.1	102.60	10.26	22.14	2.214	84	8.4	6.96
19.6	103.55	10.355	22.41	2.241	84.35	8.435	7.01
20.2	104.52	10.452	22.53	2.253	84.8	8.48	7.06
20.8	106.07	10.607	23.11	2.311	85.93	8.593	7.17
22.0	107.17	10.717	23.74	2.374	86.7	8.67	7.25
22.5	107.78	10.778	23.92	2.392	86.94	8.694	7.29

UWC – L20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.4	1.99	0.199	3.15	0.315	1.88	0.188	0.19
0.6	3.15	0.315	4.77	0.477	3.19	0.319	0.32
0.7	3.67	0.367	5.44	0.544	3.55	0.355	0.36
1.4	5.38	0.538	8.12	0.812	4.88	0.488	0.51
1.6	6.55	0.655	8.79	0.879	5.01	0.501	0.58
1.9	7.52	0.752	9.78	0.978	5.25	0.525	0.64
4.8	10.32	1.032	12.28	1.228	6.29	0.629	0.83
7.1	11.91	1.191	13.82	1.382	7.24	0.724	0.96
8.5	12.53	1.253	14.28	1.428	7.34	0.734	0.99
9.9	13.32	1.332	14.95	1.495	7.69	0.769	1.05
12.4	14.19	1.419	16.31	1.631	8.3	0.83	1.12
13.2	14.67	1.467	16.44	1.644	8.72	0.872	1.17
13.9	14.72	1.472	16.91	1.691	9.04	0.904	1.19
14.8	15.23	1.523	17.14	1.714	9.23	0.923	1.22
15.5	15.29	1.529	17.57	1.757	9.35	0.935	1.23
16.3	15.60	1.56	17.97	1.797	9.67	0.967	1.26
18.3	16.42	1.642	19.02	1.902	10.66	1.066	1.35
19.1	17.70	1.77	19.67	1.967	11.06	1.106	1.44
19.6	18.00	1.8	19.89	1.989	11.54	1.154	1.48
20.2	18.31	1.831	19.97	1.997	11.64	1.164	1.50
20.8	18.39	1.839	20.93	2.093	11.86	1.186	1.51
22.0	18.49	1.849	21.43	2.143	12.56	1.256	1.55
22.5	18.87	1.887	21.92	2.192	13.01	1.301	1.59

UWC – TB – G40 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.4	3.25	0.325	4.76	0.476	3.63	0.363	0.39
0.6	4.64	0.464	6.10	0.61	4.82	0.482	0.52
0.8	5.52	0.552	6.91	0.691	5.72	0.572	0.60
1.4	9.94	0.994	11.17	1.117	9.59	0.959	1.02
1.6	11.26	1.126	12.43	1.243	10.75	1.075	1.15
1.9	13.33	1.333	14.39	1.439	12.73	1.273	1.35
4.8	32.00	3.2	35.25	3.525	29.65	2.965	3.23
7.1	42.80	4.28	47.00	4.7	37.47	3.747	4.24
8.5	46.95	4.695	50.53	5.053	40.02	4.002	4.58
9.9	50.53	5.053	53.29	5.329	41.93	4.193	4.86
12.4	54.97	5.497	56.42	5.642	44.28	4.428	5.19
13.2	56.37	5.637	58.02	5.802	45.14	4.514	5.32
13.9	57.14	5.714	58.65	5.865	45.74	4.574	5.38
14.8	58.54	5.854	59.73	5.973	46.49	4.649	5.49
15.5	59.12	5.912	60.07	6.007	46.85	4.685	5.53
16.3	59.95	5.995	60.74	6.074	47.31	4.731	5.60
18.3	62.10	6.21	62.50	6.25	48.77	4.877	5.78
19.1	62.43	6.243	62.92	6.292	48.92	4.892	5.81
19.6	62.79	6.279	63.24	6.324	49.17	4.917	5.84
20.2	63.24	6.324	63.50	6.35	49.42	4.942	5.87
20.8	63.81	6.381	63.88	6.388	50.02	5.002	5.92
22.0	64.60	6.46	64.85	6.485	50.56	5.056	6.00
22.5	64.89	6.489	65.09	6.509	50.6	5.06	6.02

UWC – TB – F20 (91 days)							
Sample	**A**		**B**		C		**Average Water intake/unit area (Kg/m^2)**
Time ($h^{0.5}$)	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	**Water intake (g)**	**Water intake/unit area (Kg/m^2)**	
0.0	0.00	0	0.00	0	0	0	0.00
0.4	4.57	0.457	3.61	0.361	3.24	0.324	0.34
0.6	7.70	0.77	6.15	0.615	5.54	0.554	0.58
0.8	9.06	0.906	7.75	0.775	6.9	0.69	0.73
1.4	15.03	1.503	11.69	1.169	11.24	1.124	1.15
1.6	17.30	1.73	13.14	1.314	12.67	1.267	1.29
1.9	20.50	2.05	14.54	1.454	14.44	1.444	1.45
4.8	54.85	5.485	21.65	2.165	24.23	2.423	2.29
7.1	82.64	8.264	24.13	2.413	28.38	2.838	2.63
8.5	97.19	9.719	25.19	2.519	30.23	3.023	2.77
9.9	111.33	11.133	26.13	2.613	31.81	3.181	2.90
12.4	130.89	13.089	27.67	2.767	34.02	3.402	3.08
13.2	134.20	13.42	28.10	2.81	34.91	3.491	3.15
13.9	137.53	13.753	28.79	2.879	35.55	3.555	3.22
14.8	140.16	14.016	29.31	2.931	36.12	3.612	3.27
15.5	141.34	14.134	29.64	2.964	36.41	3.641	3.30
16.3	142.85	14.285	29.93	2.993	36.89	3.689	3.34
18.3	145.39	14.539	31.53	3.153	38.51	3.851	3.50
19.1	145.75	14.575	31.79	3.179	39.04	3.904	3.54
19.6	145.83	14.583	32.16	3.216	39.22	3.922	3.57
20.2	145.92	14.592	32.54	3.254	39.48	3.948	3.60
20.8	146.39	14.639	33.16	3.316	40.14	4.014	3.66
22.0	146.56	14.656	33.68	3.368	40.8	4.08	3.72
22.5	146.72	14.672	34.37	3.437	41.2	4.12	3.78

Appendix 9 Cement Content and water/cement Ratio for Equivalent Strength PC Mixes

Appendix 9 Cement Content and water/cement Ratio for Equivalent Strength PC Mixes

Table A9-1 Cement content and water/cement ratio for equivalent PC mixes

Mix No.	Mix Ref.	ECO_2 (kg CO_2/m^3 concrete)	ECO_2 / strength (kg CO_2/MPa)			Equivalent strength PC mixes cement content (kg/m^3) (water/cement ratio)		Equivalent strength PC mix ECO_2 (kg CO_2/m^3 concrete)	
			3	28	91	28	91	28	91
1	SCC-C	475	9.57	7.95	6.77				
2	SCC-L10	431	9.90	7.54	5.80				
3	SCC-L20	386	10.70	8.22	5.84	390 (0.50)	476 (0.41)	356	434
4	SCC-L30	342	11.49	6.91	5.31				
5	SCC-G20	386	8.88	6.50	5.25				
6	SCC-G40	298	9.21	4.75	4.26	500 (0.39)	500 (0.39)	457	457
7	SCC-G60	209	8.36	4.54	3.43				
8	SCC-G80	121	5.53	2.74	2.51				
9	SCC-F20	380	8.74	6.73	5.35	443 (0.44)	500 (0.39)	405	457
10	SCC-F40	285	9.54	5.68	4.66				
11	SCC-F60	191	15.63	6.81	5.13				
12	SCC-F80	96	26.70	12.65	6.72				
13	SCC-TB-G20	316	10.15	5.83	4.12				
14	SCC-TB-G40	245	9.41	4.51	3.34	443 (0.44)	513 (0.38)	405	469
15	SCC-TB-G60	174	7.83	3.53	2.77				
16	SCC-TB-G80	103	5.42	2.45	2.05				
17	SCC-TB-F20	309	9.26	4.72	4.21	513 (0.38)	513 (0.38)	469	469
18	SCC-TB-F40	232	12.70	5.56	4.54				
19	SCC-TB-F60	155	18.50	6.07	4.49				
20	SCC-TB-F80	78	37.36	11.71	7.69				
21	FC-C	404	10.10	7.23	6.13				
22	FC-L20	329	11.11	7.06	6.14	375 (0.52)	382 (0.51)	342	349
23	FC-G40	254	10.54	4.93	4.23	398 (0.49)	415 (0.47)	363	379
24	FC-F20	324	15.05	8.45	6.76	331 (0.59)	336 (0.58)	307	307
25	FC-TB-G40	208	11.33	4.88	4.14	355 (0.55)	368 (0.53)	324	336
26	FC-TB-F20	264	14.23	7.63	5.98	320 (0.61)	336 (0.58)	292	307
27	UWC-C	434	10.40	7.09	6.61				
28	UWC-L20	353	12.55	8.43	7.48	355 (0.55)	361 (0.54)	324	330
29	UWC-G40	272	12.66	6.15	4.82	368 (0.53)	390 (0.50)	336	356
30	UWC-F20	347	10.77	7.29	5.86	382 (0.51)	415 (0.47)	349	379
31	UWC-TB-G40	224	12.08	4.83	4.15	382 (0.51)	390 (0.50)	349	356
32	UWC-TB-F20	283	13.91	8.71	6.22	300 (0.65)	336 (0.58)	274	307