The effect of different Ordinary Portland cement binders, partially replaced by fly ash and slag, on the properties of self-compacting concrete

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Declaration

I, Omar Mohamed Almuwbber, declare that this research thesis is my own unaided work. It is being submitted for the MTech Degree at Cape Peninsula University of Technology, Cape Town. It has not been submitted before for any degree or examination in any other university.

(Signature) Omar Mohamed Almuwbber

Signed in Cape Town this 8th day of July 2015

Abstract

Self-compacting concrete (SCC) is a flowable self-consolidating concrete which can fill formwork without any external vibration. A self-compacting concrete mix requires the addition of superplasticiser (SP), which allows it to become more workable without the addition of excessive water to the mixture. The effect of different CEM I 52.5N cements produced by one company at different factories on self-compacting concrete was investigated. The properties of SCC are highly sensitive to changes in material properties, water content and addition of admixtures. For self-compacting concrete to be more accepted in South Africa, the effect that locally sourced materials have on SCC, partially replaced with extenders, needs to be investigated. The European guidelines for SCC (2005) determined the standard, through an extensive study, for the design and testing of self-compacting concrete. Using these guidelines, the properties of self-compacting concrete with the usage of local materials were investigated.

The effect on SCC mixes was studied by using four cements; two types of SPs – partially replaced with two types of fly ash; and one type of slag. Mix design and tests were done according to the European Specification and Guidelines for Self-Compacting Concrete (2005). Using locally sourced materials (different cements, sand, coarse aggregate, fly ashes and slag), mixes were optimised with different SPs. Optimisation was achieved when self-compacting criteria, as found in the European guidelines, were adhered to, and the binders in these required mixes were then partially replaced with fly ash and slag at different concentrations. Tests done were the slump flow, V-funnel, L-box, sieve segregation resistance as well as the compressive strength tests. The results obtained were then compared with the properties prescribed by the European guidelines.

The cements reacted differently when adding the SPs, and partially replacing fly ash and slag. According to the tests, replacing cement with extenders – in order to get a sufficient SCC – seemed to depend on the chemical and physical properties of each cement type, including the soluble alkali in the mixture, C_3A, C_3S and the surface area. The range, in which the concentration of these chemical and physical cement compounds should vary – in order to produce an acceptable SCC partially replaced by extenders – was determined and suggested to the cement producer.

The main conclusion of this project is that cement properties vary sufficiently from factory to factory so as to influence the performance of an SCC mix. The problem becomes even bigger when such cements are extended with fly ash or slag, and when different SPs are used. When designing a stable SCC mix, these factors should be taken into account.

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DEDICATION

To the soul of my father, Mr Mohamed Almuwbber.

To my dearest mother – Mrs Mabrouka Emhemed Ibsisa – for supporting me emotionally and for always struggling and sacrificing to ensure I am where I am today.

To my brothers, sisters and nephew – whom I love very dearly – thank you for being a blessing to me, and may Allah grant you the desires of your heart.

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Nomenclature

Constants

H	Height (mm)
H1	Mean depth of concrete on the vertical side of the L-box (mm)
H2	Depth of concrete immediately behind gate (mm)
PA	Passing Ability
R	Reproducibility
r	Repeatability
S	Slump flow spread (mm)
SR	Segregation Resistance
T_{500}	Slump flow time (sec)
t_v	Flow rate (sec)
W/C	Water Cement Ratio
Wc	Weight of the poured concrete sample (g)
Wp	Weight of pan (g)

Terms and concepts

ASTM	American Society for Testing and Materials
CVC	Conventional vibrated concrete
EFNARC	The European Federation of Specialist Construction Chemicals and Concrete Systems
EN	European standard
MSDS	Material safety data sheet
PPC	Pretoria Portland cement
SCC	Self-compacting concrete
SF	Slump flow class
SR	Sieve segregation class
VF	V-funnel Class
VMA	Viscosity modifying agent

CHAPTER 1

Chapter 1 Introduction

Self-compacting concrete is relatively new to South Africa, and the local construction industry has not yet fully taken advantage of it. This may be due to a lack of technical knowhow and information about self-compacting concrete. Consequently this study was done to correlate the effect of different extender types, and to quantify the effect on a corresponding mix design. The effect of different extender types on a SCC mix has been determined and evaluated in this project in accordance with the European standard.

1.1 Background and Motivation

In 1988, Japanese researchers introduced self-compacting concrete (SCC) as concrete that flows under its own weight and can be easily compacted without mechanical vibration, to achieve durable concrete. Since then, various investigations have been carried out in Japan, USA and around Europe to validate the effectiveness of this type of concrete in practical structures as mostly used in precast work (Ouchi & Hibino, 2005).

Due to its advantages (high early strength, durable structures and easy placement), self-compacting concrete is widely used in the precast concrete industry to form complex architectural designs. Limited research is available to correlate the effect of different binder (cement) types and to quantify the effect on a corresponding mix design. The influence of different PPC binder types on the characteristics of SCC needs to be investigated and evaluated in accordance with the European standard. There is a lack of an accurate understanding of the effect of different cement types and their appropriate mixtures. This can be responsible for poor quality SCC and can lead to segregation; it can also affect flowability and workability of the concrete. The addition of fly ash and slag (in that order) can improve the workability and resistance to sodium and magnesium attacks of SCC. Furthermore, it can be used for economic benefits, as cement costs more than the mineral extenders (Uysal and Sumer, 2005).

1.2 Research Problem

Cement is a material consisting of a number of constituents which interact with each other and the surroundings in various ways. There are many different types of cement on the market with different properties (Vikan, 2005). This unfortunately is not the case since raw materials are drawn from natural deposits; and large variations are encountered in the minor compounds such as magnesia, titanium, sodium, potassium, chlorides, etc. All these elements have an effect on the development characteristics of the cement and also on subsequent processes such as hardening of concrete. Moreover, mix design of self-compacting concrete (SCC) is still not properly understood; therefore, there is a need to investigate the effect of different types of Pretoria Portland cement to evaluate the effect of mix design on the properties of SCC.

1.3 Research question

What is the effect on SCC of four OPC Cem I 52.5N binders produced at different factories, extended by fly ash and slag, on the properties such as flow ability and segregation resistance?

1.4 Objectives and outcomes

The aim of this work was to evaluate the effect of different OPC binders – based on their particle-size distribution and chemical composition – on an required SCC base mix; the base mix had two types of superplasticisers, and was extended with two types of fly ash and one slag type.

The objectives were to determine:

- The required amount of additives (superplasticiser) to optimise the base mix design.
- The sensitivity to variation in limestone concentration.
- The effect of replacing the cement with different concentrations of fly ash for two types.
- The effect of replacing the cement with different concentrations of slag.
- The evaluation of the performance of the SCC according to European guidelines.
- The required range of cement compound and physical properties of cement when replaced by different extenders in the presence of SP1 and SP2.

The outcomes of this research:

- The optimum amounts of superplasticisers required were determined for each cement type to achieve the SCC according to the European guidelines for SCC (2005).
- The research also facilitated the determining of SCC sensitivity with varying limestone concentration according to the European guidelines for SCC (2005).
- Different SCC properties which resulted from the replacement of cement with varying fly ash concentrations were analysed, and an informative discussion was presented.
- Different SCC properties which resulted from the replacement of cement with varying slag concentrations were analysed, and an informative discussion was presented.
- Extensive tests on SCC properties were conducted according to European guidelines for SCC to evaluate (Slump flow, V-funnel, L-box and sieve segregation tests).
- The determination of the optimum range of chemical and physical properties of cement were established with respect to the SPs used in different cement replacement.

1.5 Significance

For self-compacting concrete to be accepted by the local construction industry, cements produced at different factories should not have a marked influence on the properties of an SCC mix and when partially replaced with extenders such as fly ash and slag it should perform as set out in the European guidelines for SCC (2005) using local South African materials. This research intended to provide a better understanding of the effect of locally produced cements, extenders and chemical admixtures on the properties on an SCC mix.

1.6 Delineation

This research specifically focused on the effect of different extender types; it therefore used and tested a sufficient base mix of four cements CEM I 52.5N (OPC) in a controlled environment. The base mix included aggregates (sand and 13 mm crushed aggregate), two superplasticisers: SP1, or SP2 and limestone.

The following extender types were used:

- Fly ash 1 (FA1)
- Fly ash 2 (FA2)
- Slag

The effect of the extender types in conjunction with the effect on the characteristics of SCC was evaluated. These properties were considered: the flowability, passing ability, viscosity and resistance to segregation. The testing methods used to determine the effect of the extender types were the slump flow, V-funnel, L-box, sieve segregation and the compressive strength tests – in accordance with the European standards.

1.7 Methodology

Experimental research was used in this project to establish optimum mix design for SCC, using materials currently available in South Africa. Testing was done and evaluated in accordance with test methods as specified in the European standard.

Data

The optimum mix-design in terms of superplasticiser and limestone was determined. Testing methods included the slump flow, V-funnel, L-box, sieve segregation and the compressive strength tests in accordance with the European standards. The data was captured and evaluated in conjunction with the limits as set out in the European standard (EFNARC, 2005).

Equipment

New instruments as per European standard specifications were purchased for the project. The instruments used included a slump cone and base plate; V-funnel with stand; L-box; and a sieve set. The PPC laboratory was fully equipped including a concrete mixer; compressive testing instrument; and curing facility. The laboratory used was climate controlled, and the instruments were calibrated.

1.8 Organisation of thesis

Chapter 1 – Introduction

The first chapter gives an overview of the project, including the background of how the project was initiated. It includes the research problem, research question, objectives and research method used.

Chapter 2 – Literature review and theory

This chapter provides an in-depth overview of the research. The literature review also takes note of the most recent research articles on different extender effects on SCC properties. Most of the work reviewed also mentions the effect of different superplasticiser types.

Chapter 3 – Research methodology

The research methodology used to solve the project's research problem is described in this chapter. Each testing procedure and specification is described in detail.

Chapter 4 – Results

Results obtained from the experimental testing are presented and discussed in order to determine the outcome of the research.

Chapter 5 – Discussion

Results and data obtained is analysed and compared in this chapter, giving an overview of what was found in the study.

Chapter 6 – Conclusions and recommendations

The main findings are summarised and concluded. Recommendations for possible future extensions of this research are identified.

CHAPTER 2

Chapter 2 Literature review and theory

The following factors are reviewed in this chapter: the literature pertaining to the advantages and disadvantages of SCC; materials required; mineral extenders; mix design; fresh and hardened properties; and testing of self-compacting concrete.

2.1 Introduction

Self-compacting concrete (SCC) is a material that varies substantially from conventional concrete. The characteristic which makes it a unique and versatile product is its ability to fill formwork under its own weight and enclose all reinforcement without any compaction. These properties are mainly due to the addition of superplasticisers which make the concrete flow. This in turn makes SCC more sensitive to change because of its meticulous requirements; complex mix-design and balancing yield stress; and viscosity.

2.2 History of self-compacting concrete (SCC)

In the early 1980s, the construction industry experts in Japan noticed a decline in the durability of concrete structures. In addition, there was a decrease in the quality of workmanship owing to the reduction of a skilled workforce in the construction industry, as well as increased reinforcement volumes using smaller bar diameters. Since the durability of concrete is highly reliant on the adequate compaction of concrete by skilled workers, there was a desperate need for a solution. A possible solution was a type of concrete which could fully compact into formwork under its own weight, without any compaction, improving durability – regardless of the quality of construction work. It was Professor Hajime Okamura of Kochi University of Technology that first proposed the concept in 1986, and by 1988 the first project using self-compacting concrete was completed (Ouchi & Hibino, 2005).

The use of SCC in North America grew rapidly between 2000 and 2002, from a minor production to more than one million cubic meters at the end of 2002. Though it has been the subject of numerous researches, SCC still requires much research. Unlike conventional concrete which has been used for a long time, SCC has only been in use for the past 30 years: there is still only a partial understanding of its properties. SCC was first used in South Africa in 2002 in the construction of the Nelson Mandela Bridge in Johannesburg. It was also used in the upgrade of the Soccer City Stadium in Soweto which formed part of the 2010 Soccer World Cup initiative. SCC was also used in the Gautrain project, linking OR Tambo Airport to Johannesburg Central and the city of Pretoria (Haldenwang & Fester, 2009).

2.3 Properties of SCC

SCC is a type of concrete designed to flow freely around obstacles, and can be transferred to formwork; it also encloses all the reinforcing bars, without bleeding and segregation. This type of concrete does not require any mechanical vibration, and it still meets all the requirements of a conventional concrete (De Schutter & Boel, 2007).

2.4 Benefits of using SCC

The most important benefit of using SCC is that there is no need for compaction of fresh concrete. This reduces the required energy in placing and using the concrete. There is a significant reduction in the time required for construction, and in the workload of the workers because the placing process is easier and faster. This is seen in the example of the construction of the Akashi-Kaikyo Bridge, where the use of SCC reduced the total project duration from 30 to 24 months.

The high flowability of SCC enables different placing methods, such as the pumping of concrete from the bottom of a structure; this placing method has been used in the construction of the pylons in the Nelson Mandela Bridge (Jooste, 2006). The high flowability and the fact that there is no need for compaction, make it possible to achieve special designs and shapes when using SCC; whereas with conventional concrete, there are limitations to the designs and shapes: both the manual placement of concrete and the movement of the compaction equipment are restricted. Some examples of constructions where the use of conventional concrete would not have been possible include the Science Centre in Wolfsburg, Germany, the façade of the National Theatre in The Hague and the pylons of the Nelson Mandela Bridge (Jooste, 2006). The use of SCC enables innovative construction methods. The use of congested reinforcement in design is also possible, as SCC can flow around them and there is no requirement for external consolidation.

Using SCC reduces the noise level: from about 90 dB when using conventional concrete to below 80 dB when using SCC. This leads to a safer working environment and improves communication on site. Noise levels above 80 dB can cause deafness, stress and fatigue. Therefore with low noise levels, no ear protection equipment is needed – which facilitates communication. Vibrations above 0.25 m/s^2 can cause pain and stiffness of the limbs, back and neck. A serious condition caused by the continuous use of the poker vibrator (with vibration between 0.75 and 4 m^2/s) is known as 'white fingers' which affects the workers' blood circulation (Skarendahl & Petersson, 2000).

The use of SCC also reduces the risk of air voids, therefore leading to increased concrete strength and density. Furthermore, its use leads to an increased bond between the concrete and the reinforcing steel and less chance of bleed water formation below the reinforcing and aggregates. There is also a reduced chance of honeycombing and blow holes which provides an excellent off-shutter finish. A thorough mixture is achieved by the use of admixtures which ensures that all the cement particles are well dispersed throughout the mixture, therefore producing a more homogeneous concrete (De Schutter *et al.,* 2008).

SCC is well-suited based on its properties for the production of high quality precast elements while reducing energy consumption in the process. The energy involved includes the power to operate equipment, as well as the labour and equipment efficiency. The cycle time of the moulds is also reduced because the admixtures used in the mixture can accelerate the hydration process, therefore accelerating the strengthening process. SCC also reduces the wear of mixing equipment, which leads to less need for maintenance (De Schutter & Boel, 2007).

2.5 Disadvantages of using SCC

The biggest disadvantage of using SCC is the cost involved in the production of this type of concrete. SCC costs more than conventional concrete, as there is the necessity to use admixtures. The cost involved in setting up the plant can be higher as well (Bouzoubaa & Lachemi, 2001).

Another disadvantage is the smaller-sized aggregates. Also, a large amount of fillers and fine materials need to be used in order to avoid segregation. SCC is particularly sensitive to variation of aggregate; therefore this must be closely controlled to ensure consistency in quality and grading.

Due to its high sensitivity, strict measures to ensure quality at the batching and mixing operations are required. A narrow specification must be met for any material to be used in the mix; to control the homogeneity of the mixture in terms of SCC properties sands must be carefully washed and graded. If parameters such as workability and filling ability are not carefully monitored, they can affect the water demand. There is therefore a possibility of obtaining a mixture that easily segregates or is less flowable. The sensitivity of SCC must be taken into account by any contractor using SCC, and proper on-site quality control tests should be provided (Gesoglu *et al.,* 2009).

Special formwork is also required when working with SCC. The formwork needs to be strong enough to support the concrete in its early stages as the form pressure of SCC is generally higher than that of conventional concrete. When SCC is used, the formwork must be watertight to prevent any water and fines loss from the SCC mixture (De Schutter *et al*., 2008).

2.6 International applications

The building of the anchorage of the Akashi-Kaikyo Bridge is one of the early important projects – the use of SCC was effective in reducing the construction duration from 30 to 24 months. The Akashi-Kaikyo Bridge is 83 m long, 63 m wide and approximately 45 m high. This provides a good example of the effectiveness of SCC in reducing the construction period (De Schutter *et al.,* 2008).

Another good example of the advantage of using SCC is in the construction of the 0.8 m thick wall of the liquid natural gas tank at Osaka Gas Company, where the duration of the project was reduced from 22 to 18 months. One of the works consisted of casting without a pump and allowing free-fall of SCC into the formwork and linings (Bouzoubaa & Lachemi, 2001).

The Burij Khalifa in Dubai is the tallest building in the world at the moment. During its construction the most recent accomplishments in all fields were united, including concrete production technology. Several SCC mixes were specially designed so that the concrete could be pumped to record heights in this project. It was necessary to pump and place 230 000 m^3 of SCC (OkrajnovBajić & Vasović, 2009).

The use of SCC in Sweden has risen to about ten percent of the total concrete production in 1999 (Domone, 2006). One of the major projects conducted with the use of SCC, involved the construction of a bridge using various materials as fillers. This work was conducted in the USA in 1998, and marked the first use of SCC for an entire construction project outside Japan (Domone, 2006).

SCC has ever since been used worldwide in various constructions such as monolithic frame bridges, box tunnel monoliths, frame supports and many more (Kuder *et al.,* 2012). SCC is preferred particularly in the precast concrete industry. In countries such the Netherlands, SCC is exclusively used in some precast industries. This extensive use has led to much gained experience and an increase in the use of SCC in precast slabs, beams, columns, arches and bridges. In special cases, SCC has also been used in-situ. The façade of the National Theatre in The Hague was one of the first projects where only SCC could be used in the small ribs of 8 mm deep. The presence of congested reinforcement and the possibility of pumping SCC, have motivated the use of SCC in some tunnel wall projects. SCC has also been used in projects where homogeneous watertight structures are required such as the construction of heavily reinforced walls for a fish pond in the Rotterdam Zoo. Another example of SCC use in the Netherlands is the construction of the bridge piers for the South Tangent traffic connection between Haarlem and Amsterdam. The shape and the design of this structure were such that only SCC could have been used. One of the advancements in the use of self-compacting reinforced concrete is in the Netherlands where it is used in lighter and thinner floor elements (De Shutter *et al.,* 2008).

2.7 Cement

Cement is widely used in construction and is mainly composed of clinker, which makes up approximately 95 percent of the material. The clinker consists mainly of calcium oxide, silica, alumina and iron oxide. In nature, cement occurs in either primary or secondary form. Primary cement is available in nature while secondary cement is obtained from rocks such as dolomite or dolerite. Clays from which cement is derived are formed from the weathering of rocks. Shale is a type of clay which has been subjected to high pressure and temperature over a very long time and therefore has different physical properties, but similar chemical properties to clay.

Owing to the fact that cement is obtained from materials which form over a long period of time, the chemical composition of various types of cement from different geographical origins is rarely the same. Therefore quality control is required to assess the value of the raw material (Mantel, 1991).

2.7.1 Types of cement

There are several types of cement; however, only five types of cement based on the ASTM (American Society for Testing and Materials) will be discussed:

Ordinary Portland cement

Ordinary Portland cement or OPC is the basic cement type. It consists of a larger particle size and lower hardening or strength development compared to other Portland cements. It is suitable for use in general construction when specific properties are not required.

Rapid-hardening Portland cement

Rapid-hardening Portland cement or RHC has the same chemical composition as OPC, however in order to achieve the fast strength development, the Rapid-hardening cement consists of finer particles compared to Ordinary Portland cement. This type of cement is useful for repair works, construction in cold weather and early de-moulding. Aiad (2003) reported that a high concentration of C_3S and C_3A increases the rapid-hardening property of cement.

Sulphate-resistant Portland cement

This type of cement has a controlled chemical composition which ensures that the C_3A content does not exceed 3.5 percent of the total mixture as C_3A is highly vulnerable to attack by calcium sulphate. Calcium hydroxide formed during hydration, reacts with sulphate ions in solution to form gypsum. The C_3A then reacts with the gypsum to form different types of calcium sulpho-aluminate hydrates such as ettringite. Given the large specific volume of these hydrates formed compared to reactants, there is expansion of the hydrates in the mixture which leads to progressive destruction of the concrete. In order to obtain cement with a reasonable strength development, the sulphate-resistant cement is ground to a particle size below Ordinary Portland cement but above that of the Rapid-hardening cement. The effect of reduced particle size on the hardening of the cement is that a larger surface area becomes exposed to the hydrating water, therefore increasing the hydration rate of the cement and improving the strength development.

Low-Heat Portland cement

This type of cement generates less heat during hydration; therefore strength increase is slower. This is achieved by using a maximum amount of C_3S and C_3A and a minimum amount of C_2S. This type of cement is more suitable for use in mass-concrete and in construction during hot weather.

Modified Portland cement

Modified Portland cement is suitable for the use in general construction work. The key difference between Ordinary Portland cement and Modified Portland cement is the slight sulphate resistance of the Modified Portland cement due to the low content of C_3A (less than eight percent). The reduction of the amount of C_3A leads to the lower rate of reaction which in turn reduces the production of the heat of hydration in early stages. This type of concrete is suitable to be used in small-scale concrete projects such as retaining walls.

The four Ordinary Portland cements that were used in this study, were produced in different PPC factories according to the European standard EN-197-1 and are all labelled as CEMI 52.5N.

2.8 Mineral extenders (fillers)

2.8.1 Fly ash

Fly ash derives from the non-combustibles obtained from burning finely ground coal in the boilers of modern power stations. The combustibles burn to produce heat, required to produce steam, and the non-combustibles form fly ash (Siddique, 2011). During combustion at high temperatures, fly ash is in the liquid state and upon cooling solidifies to form small hollow spheres. The fly ash is removed from the boiler along with the combustion gas, and is removed from the gas stream subsequently precipitated.

Siddique (2011) has shown that the quality of fly ash is related more to the burning conditions in the boiler and on the fineness of the fly ash rather than the chemical composition of the fly ash.

Fly ash particles react with calcium hydroxide during hydration of C_3S and C_2S in the clinker. This reaction creates products such as calcium silicate hydrates and calcium aluminate hydrate. It has also been established that the water-reducing effect of fly ash is not the same when used with different cement types and therefore the effect of the fly ash on each specific cement type must be investigated (Siddique, 2011).

2.8.2 Slag

Slag is obtained from the reaction between silica and other contaminants in the iron ore, limestone and dolomite which have been added during the manufacture of pig iron in blast furnaces. The slag is further cooled down and a fast-running motor breaks the streams either into small particles or pellets. The fully crystallised, slowly air-cooled blast-furnace slag has no hydraulic properties and is therefore considered as inert. However, both granulated and pelletised slag has higher glass content because of the sudden drop in temperature during the granulation or pelletisation process. The glass content is what is responsible for the hydraulic properties of the slag. Therefore, the glass content of the slag is very important: the optimum value of glass content is found to be around 95% (Hale *et al.,* 2008). During hydration of cement paste, the addition of slag accelerates the reaction by releasing additional acids which further react with calcium hydroxide; to form additional calcium silicate hydrate and calcium aluminates hydrate (Anastasiou *et al*., 2014).

2.8.3 Limestone

Masonry cements are produced by grinding together cement clinkers, gypsum and limestone. They are grinded to an approximate surface area of 480 m^2/kg. Hydrated lime can also be used instead of limestone as a partial or total replacement.

Limestone and lime improve the workability of the cement and also act as water retention agents, which prevent faster drying of the cement when it is used for the purpose of plastering (Bouzoubaa, 2007).

The water/powder (cement, fly ash, limestone filler, silica fume, etc.) ratio of mortar and the type of chemical admixtures should be determined, in order to place the fresh mortar without any external compaction and at the same time without causing any segregation (Felekoğlu *et al*., 2006).

2.9 Additives

2.9.1 Superplasticiser (SP)

Superplasticisers are chemical additives added to self-compacting cement or a self-compacting concrete, to improve the workability and to reduce the water requirements. There are various types of superplasticisers varying by their chemical compositions.

In SCC, superplasticisers are found to improve the initial workability of the mixture. However, the chemical structure of the superplasticiser and its compatibility with the paste influence the time-dependent workability of the cement paste. Superplasticisers, which are chemicals, can therefore be modified to improve their compatibility and performance with SCC. These modifications can be achieved by changing the chemical structures of the polymer, and have been shown to improve the control of the slump flow (Felekoglu & Sarıkahya, 2008).

The knowledge of using superplasticisers as dispersive admixtures in cement dates from the 1930s. Later, in the 1960s, more progress was made – with the development of sulphonated melamine formaldehydes in Germany and naphthalenes in Japan; these enabled engineers to use SPs under controlled conditions, and with more understanding (Boukendakdji *et al*., 2012).

The need to develop effective SPs – that yield a concrete with more fluidity and with a great ability to resist segregation – has pushed researchers to conceive another type of SP, based this time on polycarboxylate (PC) instead of melamine and naphthalene (Puertas *et al.,* 2005).

The difference between SPs based on polycarboxylate and the previous ones, is in the molecular structure (Puertas *et al.,* 2005). In fact, their molecules consist of only one main chain that is linear with lateral carboxylate and ether groups. It has been proven that these carboxylate groups enhance the ability of SP to be adsorbed in cement particles. The quality and duration of fluidity is related strongly to the number and lengths of lateral and main chains. That is, the shorter the main chain and the longer the lateral chains and their increased number, the greater the fluidity. This also increases the duration of fluidity. The molecular structure of polycarboxylate superplasticiser admixtures is shown in Figure 2.1

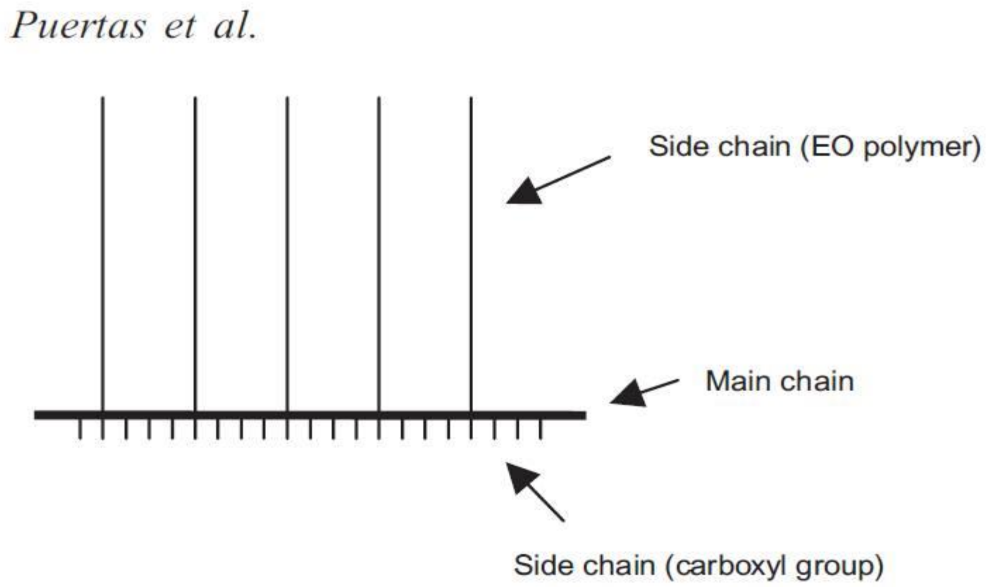


Figure 2.1: Chemical structure of polycarboxylate admixture (Puertas *et al.,* 2005)

2.10 Impact of the particle-size distribution and surface area of cement on SCC

Vikan *et al.* (2007) have demonstrated that the most important factors that have an effect on cement pastes with different chemical compositions are the water-cement ratio (W/C) and the specific surface. Water content is a critical component in a fresh concrete mix because there is a close relationship between the water content and the rheology of fresh concrete. Increasing the water content while other components of the concrete are kept constant, leads to a decrease in yield stress and viscosity of fresh concrete; eventually resulting in more bleeding and segregation of the concrete (Tregger *et al.,* 2010).

It has been observed by Libre *et al.* (2010) that several factors contribute to the varying fluidity of SCC. For example, increasing the W/C ratio by approximately 10% can increase the slump flow by about 18%. Moreover, the addition of 1% of SP by mass of binder can improve the fluidity of the mortar by up to 30%. The use of limestone powder has a great impact on the fluidity of cement paste with a lower W/C ratio.

The spherical shape of fly ash particles also effects the reduction of the friction between aggregate and paste, which allows this mineral admixture to improve the fluidity of SCC (Libre *et al.,* 2010).

The type of superplasticiser also influences the flow properties of cementitious pastes, introducing retarding effects on the cement paste. Additionally, cement paste chemistry and various dispersing mechanisms also influence the overall effect of the superplasticiser.

Vikan *et al*. (2007) discusses the effect of varying the superplasticiser dosage and type on the rheology of cement pastes with superplasticiser dosages ranging from 0–2% (by weight). The flow resistance is presented as a function of cement fineness for the four cements. The cements used originate from the same clinker and thus have a relatively similar flow resistance. This means that cement cannot be treated as an unvarying material. Furthermore, Vikan *et al.* (2007) showed that properties of cement such as fineness, content of C_3A and alkali greatly affected the flow resistance. These factors might increase or decrease the flow resistance value depending on the type of cement used. The authors presented a correlation between the flow resistance and Blaine value when multiplied with cubic C_3A and C_3S. The relationship focused on the cubic C_3A crystal modification, since it is known to be more reactive than the orthorhombic crystal modification. Figure 2.2 illustrates this correlation. Furthermore, adding plasticiser retards cement hydration. The extent of retardation is dependent on plasticiser type and dosage, as well as cement type.

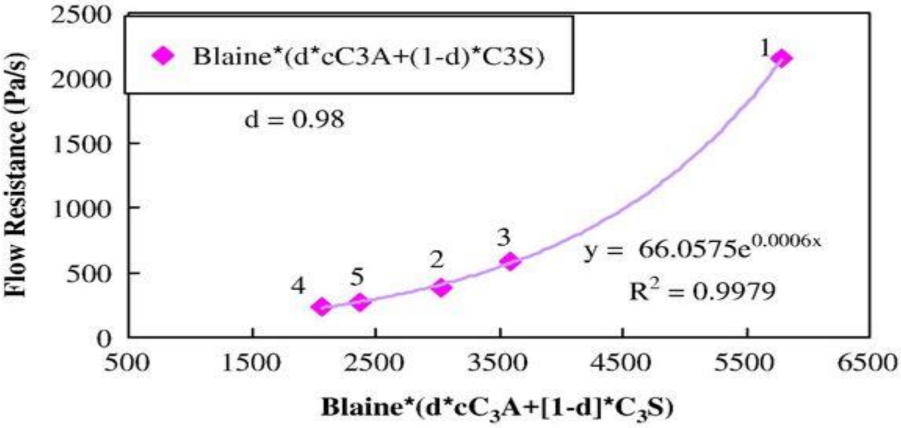


Figure 2.2: Correlating the Blaine value, multiplied with a weighted sum of cubic C_3A and C_3S for cements (Vikan *et al.,* 2007).

Particle-size distribution (PSD) of cement has caught researchers' attention over the years due to its impact on cement properties. There is a relationship between the rate of hydration, the packing density and the PSD. According to Aiqin and Ningsheng (1997), it has been proven that the narrower the PSD of cement, the faster the rate of hydration. Furthermore, Ferraris *et al*. (2001) have shown that cement paste properties depend on the porosity within the paste, whereas the porosity itself depends on the packing density as well as the rate of hydration. It is reasonable to say that there will be no significant porosity in a case where there is higher packing density. With the same reasoning, a higher degree of hydration will result in a lower porosity.

A mathematical model for describing PSD and packing density was proposed by Aiqin and Ningsheng (1997), which shows that a wide PSD is beneficial in increasing the packing density, whereas a homogeneous distribution causes an increase in the degree of hydration. They suggested that a suitable distribution of particles should follow this relationship expressed by d1/d2 = 0.3 where d1 and d2 are the diameters of the smallest and largest particle respectively.

In a study conducted by Zhang and Munn (1995), it was established that factors such as fineness and specific surface area define and control the compressive strength of cement paste. For identical surface areas, cement with a narrow particle-size distribution has a higher strength than cement with a wide-size distribution. It is preferable in industry to express the fineness of cement by surface area rather than particle-size distribution. Cement fineness influences the strength of cement paste at a very early age – one to three days. The reason for this is that the hydration at this point depends more on the surface area of particles upon which water will act in the mix. The chemical composition of cement contributes to the compressive strength of cement paste. That is why cement with higher C_3S content gains strength quicker than that with higher content in C_2S, as can be seen in Figure 2.3. In OPC (10–11 %) C_3A will contribute to strength only at a very early age, whereas C_4AF will not contribute to strength at all.

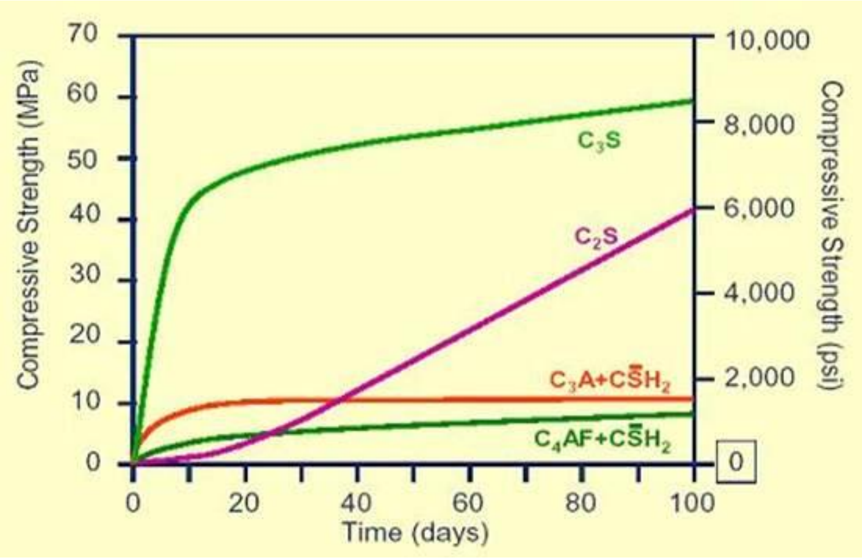


Figure 2.3: Development of strength of pure compounds (Taylor, 1977)

There are models that were proposed by Taylor (1977) involving chemical compounds of cement, but these models were deemed inefficient and a new approach for predicting the compressive strength was developed as for Equation (2.1):

$$F28(\%) = 3C_3S + 2C_2S + C_3A - C_4AF \qquad (2.1)$$

(F28 = compressive strength at 28 days)

The most important factor that defines the proportion of fine and coarse particles in the cement is the PSD (Celik, 2009). The water demand, setting and hydration reactions all depend on this distribution. The effect of particle size on the strength of cement paste has been reported to be in the range of 0 to 30 µm, and above 60 µm particles will only have a filling effect thus will not contribute to the cement paste strength. Celik (2009) reported that the better range of specific surface area for cement should be 2 500–3 000 cm^2/g. He also stated that a packing density is increased as the PSD widens, whereas a narrow PSD gives a higher rate of hydration for the same specific surface area (SSA).

2.11 Impact of mineral extenders on SCC

In recent years, there has been an increase in the use of SCC in various construction works. The main difference between SCC and conventional concrete is the importance of the use of admixtures with the purpose of improving the workability of the concrete. Many studies have shown the advantage of the use of admixtures on the properties of SCC (Uysal & Yilmaz, 2011). These studies show that the use of admixtures improved the workability of the concrete while reducing the cement content.

As mentioned, one of the disadvantages of SCC is its production cost. The reduction of this cost is done by introducing extenders such as silica fume, fly ash and ground granulated blast-furnace slag. These extenders have the role of improving the fluidity of concrete by reducing the amount of SP required to produce a concrete with slump flow similar to concrete containing only cement. These fine extenders are used to enhance the particle-size distribution and particle-packing density (Boukendakdji *et al.,* 2009).

According to Sukumar *et al*. (2008), the use of extenders – such as fly ash – facilitates better flow characteristics of the cement. The extenders are able to improve particle packing, and decrease the permeability of the concrete. This has an effect of increasing the durability of the concrete. As mentioned in the previous section, the main extenders and fillers used in SCC are industrial waste by-products such as limestone, fly ash, and blast-furnace slag; they all improve the workability of SCC. If the amount of these materials can be increased, this has the added benefit of reducing environmental pollution (Uysal & Yilmaz, 2011).

In the work conducted by Uyasal and Sumer (2011) and Uyasal *et al.* (2012) on the performance of self-compacting concrete with mineral extenders, it was found that fly ash and granulated blast-furnace slag significantly increased the workability and the compressive strength of SCC at 28 days. This work also concluded that another advantage of using extenders is the increase in sodium and magnesium resistance with the best resistance obtained when 40% slag and 60% Portland cement is used (Uyasal & Sumer, 2011).

Gesoglu *et al.* (2009) analysed the effect of binary, ternary and quaternary blends of cement with fly ash, slag and silica fume. The slump flow results indicated a better performance for ternary and quaternary blends compared to binary ones because of the combined effects of the extenders on the cement particles. Furthermore, it was shown that a ternary blend of slag and silica fume provided, improved the durability of concrete.

It has been proven that the incorporation of high-volume mineral extenders decreases the heat of hydration and improves rheological properties. The use of fly ash is beneficial as it also reduces the utilisation of VMAs (Viscosity Modified additives) (Nuruddin *et al.,* 2014).

The use of mineral extenders, however, causes some deleterious effects such as the retardation in the setting time and low early strength. In some cases, the combination of mineral extenders is used as a solution to this problem since it can help improve the filling and passing ability of SCC (Gesoglu *et al*., 2009).

2.11.1 Effect of fly ash on SCC

The high slump flow of SCC is obtained by incorporating optimum dosages of admixtures to the conventional concrete. Therefore, during the design of an SCC mix, attention has to be paid to the proportion of incorporated extenders. For instance, it is convenient to increase the sand content rather than increasing the coarse aggregate content in order to prevent the occurrence of segregation. Doing so, a high volume of cement will be required having the effect of increasing the temperature and the cost of SCC production. As an alternative, VMAs have to be used in order to improve the stability of SCC. Mineral extenders such as fly ash are also used for this purpose (Bouzoubaa & Lachemi, 2001). Fly ash has been extensively used as a mineral extender in SCC. In a study conducted by Khatib (2007), fly ash was replaced from 0% to 80%, with the water-cement ratio maintained at a constant value of 0.36. It was found that replacing cement with fly ash led to an increase in the concrete’s strength and a decrease in shrinkage. When 40% cement was replaced by fly ash, the result was a compressive strength of more than 65 N/mm^2 at 56 days (Khatib, 2007). The effect of the increase of strength with the increase of fly ash content was also observed in previous work conducted by Siddique (2011).

Libre *et al*. (2010) found that replacement of cement with fly ash in fresh concrete can be used to enhance the flow ability based on to their particles’ geometrical shape and size distribution that enables it to lubricate fine particles and reduce the friction between cement particles. The replacement of fly ash causes the decrease in yield stress and viscosity values of the concrete mix. The increased amount of fly ash resulted in high absorption values; however, all concrete with fly ash exhibited absorption of less than 2%. A significant reduction in shrinkage was observed as the FA content increased. At 80% fly ash the shrinkage was reduced by two thirds compared to that presented in previous research (Khatib, 2007).

According to Lee et al. (2003), cement has a greater density than fly ash, and this prevents the cement particles from flocculating. Due to its spherical shape, fly ash has a ball-bearing effect. Fly ash with different size distribution affects the packing density of the paste, changing the fluidity of the paste. It has been established that a high fly ash content, leads to a decrease in the 28 day strength of the concrete and an increase in water absorption. Khatib (2007) found a sharp decrease in strength of concrete with increasing absorption from 1% to 2%. However, after 2%, the strength decreases at a lower rate.

According to Sukumur *et al.* (2008), the use of fly ash has benefits: such as the reduction of water requirements along with an increase in the workability and in the strength at later ages. These results were obtained for a specific cement additive ratio and the use of additional cement in the mixture did not provide similar results. Fly ash is known for its long-term strengthening effect on the concrete and durability as it provides a continuous hardening effect on the concrete. The replacement of cement with fly ash was shown to decrease the viscosity of the paste, compared to paste without extenders. At very high fly ash content, no reduction in viscosity was observed – even with the increase of rotational speed of a rheometer. Thus, fly ash is able to increase the energy required to reach the adequate workability of the concrete mix (Felekoglu *et al.,* 2006).

The use of fly ash reduces the SP dosage required in SCC to produce similar flowability compared to concrete made with Portland cement only. Fly ash is also known to improve rheological properties and reduce shrinkage owing to the heat of the cement’s hydration.

Work by Kwan and Chen (2013) showed that the replacement of cement by 30% fly ash resulted in excellent workability and significant improvement of rheological properties of concrete. Bouzoubaa and Lachemi (2001) investigated the possibility of replacing cement with high volumes of fly ash in SCC and found that the obtained concrete resulted in great flowability, cohesiveness and high compressive strength after 28 days.

Yazici (2007) replaced cement with class C fly ash in different proportions ranging from 30% to 60%. It was shown that a high volume of fly ash content especially with 10% slag furnace replacement gave a high performance of SCC. These mixtures also had good mechanical properties.

The properties of SCC containing class F fly ash were studied by Siddique (2010) who found that SCC mixes developed at 28 days a compressive strength between 30 and 35 MPa. He was able to design an SCC mix which incorporates a fly ash content of up to 35%. The SCC mixes had a slump flow range of 600–700 mm, a flow time less than 4.5 seconds and a V-funnel time in the range of 4–10 seconds. The L-box ratio for all mixes was greater than 0.8. A compressive strength greater than 50 MPa (100 mm x100 mm x100 mm) was attained at 90 days.

In fact, fly ash and slag have amorphous silica (S) which reacts with calcium hydroxide (CH) to form additional C-S-H. It is known that C-S-H is the major compound of cement hydration that is responsible for cement strength. Fly ash and slag will then contribute to the increase of cement strength since they produce additional C-S-H.

Hale *et al.* (2008) used fly ash to produce concrete with high strength and low dry shrinkage in a 50% fly ash replacement. They also found that fly ash at 40% replacement improved the workability of the mix.

They observed that cement with fly ash resulted in a greater slump than that with slag. The increase in slag reduced the slump due to the fineness of the slag cement: the finer the material, the more water will be required because of the increase in surface area per unit volume (Hale *et al.,* 2008).

2.11.2 Effect of slag on SCC

The benefit of using slag is that it is an extender with almost the same chemical composition as cement and, better yet, it is available in sufficient amounts around the world. Moreover, slag has a higher sulphate and acid resistance, better workability, lower permeability and higher corrosion; and also helps to lower the heat of hydration (Boukendakdji *et al.,* 2009).

According to Boukendakdji *et al.* (2009), replacing cement with slag was sufficient at 15%, yielding workability retention of about 60 minutes. The only disadvantage reported was that the compressive strength of SCC was decreasing at all ages with the increase of slag replacement. Previous work conducted by Kuder *et al.* (2012) reported that SCC with high volumes of slag had higher mechanical properties (compressive strength, elastic modulus, creep and shrinkage) compared to SCCs without slag.

Boukendakdji *et al.* (2012) used blast-furnace slag as an extender. They found it to have advantages for fresh self-compacting concrete. There was an observed improvement in workability of the SCC up to 20% of slag content and an optimum value of 15%. However, the strength was also shown to decrease with increasing slag content in the early stages but had less effect later on.

There was a decrease in plastic viscosity when the slag content was increased. In the case where the cement was partially substituted with vitreous powders, it was shown that the yield stress and the plastic viscosity both decreased. Similarly, semi-crystalline powders could achieve the same results and lower the viscosity, however, only in high dosages (Boukendakdji *et al*., 2012). The same results were obtained by Boukendakdji *et al.* (2009) where the optimum slag replacement of 15% gave a better workability of the cement paste.

There was an observed decrease in strength with increasing slag content. However this decrease was found to be negligible at later age – 56 to 90 days after mixing (Boukendakdji *et al.,* 2009). Investigating the properties and behaviour of SCC using fly ash and slag as admixtures at high temperatures, fly ash was shown to provide a better performance when used in cement – compared to slag (Uysal *et al.,* 2012). However, a different result was obtained in research conducted by Hale *et al.* (2008), where the effects of fly ash and slag were compared in the study of the properties of concrete mixes used in transportation infrastructure. These results indicated that slag had a positive effect on almost all the cements tested, while fly ash resulted in a mixed effect (Hale *et al.,* 2008).

According to Boukendakdji *et al.* (2012), the main reason for the flocculation of cement particles in concrete is dispersion forces - Van der Waals forces. This affects the SCC's flow properties. Dispersing additives are used to counter these forces and thus improve the flow. In trying to incorporate SP and slag in concrete so as to produce SCC, they found that the yield stress and plastic viscosity decreased when increasing the slag content at constant concentration of SP.

Kuder *et al.* (2012) reported that SCC with high volumes of slag had similar mechanical properties to conventional SCC at later ages. The similar properties included: compressive strength, elastic modulus, creep and shrinkage.

2.11.3 Effect of limestone on SCC

The use of limestone leads to an increase in the compressive strength of the concrete; this can be explained by the filling effect of the finely ground limestone (Felekoglu *et al.,* 2006). Limestone filler also provides a suitable nucleus for hydration, thereby facilitating the hydration reaction. Limestone can react with the C_3A phase, which can lead to the formation of monocarbo-aluminate. The process partially takes part in ettringite. This provides the early strength of concrete. However, it seems that no further hydration reactions take place to improve the long-term strength of the pastes. Within days of observing the strength, the pastes containing limestone show a higher compressive strength compared to those with fly ash (Felekoglu *et al*., 2006).

According to Felekoglu *et al.* (2006), all powders increase the initial viscosity as compared to plain cement paste. This effect also depends on the substitution ratio of each mineral or inert filler/extender. In the end, it was observed that in order to obtain a specific workability, a series of tests should be conducted to determine the optimum content and type of materials for each cement/mineral extender and filler/plasticiser mixture.

The powder is defined as particles with sizes less than 125µm, and in SCC it consists of Ordinary Portland cement (OPC) and fillers.

One of the ways to keep the stability of SCC is by increasing the solid fraction part of the cement paste that will result in an increase in viscosity. The powder (limestone) content is actually greater in SCC (450 to 600kg/m^3) than in conventional concrete (Ferraris *et al.,* 2001).

Ferraris et al. (2001) proved that the increase of heat in concrete is higher when using a great amount of cement. This is the reason why replacing cement with inert fine fillers is more appreciated as a part of the powder content in order to decrease the amount of cement used, consequently reducing the evolution of heat in concrete.

Particle fineness affects the rheology of cement paste and concrete; so the finer the powder, the higher the yield stress and plastic viscosity. This is a desirable characteristic, since smaller particle sizes will result in a reduced segregation ratio.

2.12 Impact of chemical admixtures (superplasticisers) on SCC

Adding superplasticiser to the cement paste and self-compacting concrete has been shown to increase the workability of the mix. However, several other parameters affecting the performance of the cement containing superplasticisers have been identified. These parameters are the chemical composition and the molecular structure of the admixture which have an influence on the rheological properties of the concrete (yield stress, viscosity and concrete slump); the chemical composition of the cement; and especially the C_3A content and availability of the soluble sulphates. The presence of other types of admixtures and hydrates formed during the early stages of hydration also influence the behaviour of the superplasticisers in concretes (Winnefeld *et al.,* 2007). Superplasticisers are particularly of great interest to the industry because of their ability to reduce the water content (Winnefeld *et al.,* 2007).

Tregger *et al.* (2010) reported that improvement of rheological parameters of self-compacting concrete is made possible by introducing some materials in the concrete mix, such as chemical admixtures. For instance, air entraining agents (AEA) and water reducing agents are mostly used to improve the consistency (that has the effect of reducing the bleeding and segregation of the concrete) and the workability of the concrete.

There are various types of superplasticisers; the differences between them are based on their chemical compositions. In research conducted by Boukendakdji *et al.* (2012), two types of superplasticisers were compared: it was found that the polycarboxylate-based superplasticiser mixed with concrete led to a better workability and higher compressive strength, compared to cases where naphthalene sulphonate superplasticiser was used. This highlighted the influence of the type of superplasticiser on the properties of the concrete. Carboxylate-type SPs will be used in this research.

Superplasticisers are used in order to enhance concrete properties in making the material become more workable; to create a lower water-cement ratio; and to reduce cost – since the optimisation of cement content can then be achieved (Puertas *et al.,* 2005).

The V-funnel test is related to the viscosity of the SCC. Libre *et al*. (2010) demonstrated that the W/C ratio effects the flow times more than the SP dosage. The relationship between the W/C ratio and the viscosity is not linear. For example, the increase of W/C ratio from 0.35 to 0.45 decreases the flow time about 77%; on the other hand, increasing W/C ratio 0.45 to 0.55 gives a reduction in flow time of about 11%.

The tests completed by Libre *et al*. (2010) show that the viscosity is affected when adding fly ash. The main factor that affects the viscosity has been found to be the W/C ratio, while other factors studied in this research, as cited above, have negligible effect on the viscosity of the mixtures. The studies continued showing that there are some VMAs that do not have an effect on the viscosity. Moreover, the molecular weight is also of great importance, as it influences the performance of SP in the cement paste: the high adsorption and high degree of fluidity produced is obtained by SP with a high molecular weight. However, SPs can sometimes have negative effects, such as the retardation of hydration that has an impact on cement morphology and microstructure (Puertas *et al.,* 2005). When using a superplasticiser based on melamine and naphthalene, the dispersion ability of SP on the fluidity of the cement mixture depends strongly on the C_3A and alkali content in the clinker; cement fineness; calcium sulphate; the introduction of SP in the mixture; etc. However, when using polycarboxylate type SPs, the fluidity will depend on the type of calcium sulphate utilised, and will be attenuated in the presence of C_3A content – lowering the fluidity of the concrete.

Over the years, superplasticisers have been used to disperse cement particles in order to improve the workability of concrete. Lignosulphonates (LS) were used more often in the past due to the advantages that they offered; and there was enough knowledge available about these admixtures. The adsorption of certain chemical admixtures depends strongly on the concentration of sulfate ions present in the cement. Also, some SCCs have class C fly ash and slag added in the mixture, which provide additional sources of sulfate and, as a consequence, the rheological properties of the cement paste is affected (Ferraris *et al.,* 2001).

In fact, a high quantity of chemical admixtures will be adsorbed and incorporated into cement hydrates if there is a low concentration of sulfate. As a result, the cement hydrates will lose their dispersing effect. Similarly, a small amount of admixture will be adsorbed if the concentration of sulfate is too high. In the case where there is a low quantity of sulfate in the cement paste mixture, the hydration of C_3A yields calcium aluminate hydrates which is responsible for flash-setting. Whereas, in the case where there is a high quantity of sulfate, the nucleation and growth of gypsum crystals will lead to a false-setting behaviour. These setting abnormalities take place most of the time in fresh cement paste or concrete (Ferraris *et al.,* 2001).

Work conducted by Zhang *et al.* (2010) found that “lignosulphonate (PLS), polycarboxylate (PC) and polynaphtalene (PN) based SPs retarded the cement hydration in proportion to the type and dosage of the admixtures used”. In a study conducted by Yamada *et al.* (1999), the authors investigated the impact of the side chain length and the degree of polymerisation of the main chain.

The longer the polyoxyentylene (PEO) side chains, the more fluidity at the same dosage; the more fluidity will decrease over time and the shorter the setting time will be. However, the shorter the main chain length, the more fluid the mix will be at the same dosage – resulting in a longer setting time. The authors mentioned that SPs will always reduce the yield stress and the plastic viscosity in proportion to the W/C ratio.

The achievement of self-compacting concrete is made possible by introducing superplasticiser into conventional concrete, since the flow properties of concrete are controlled by these admixtures. In fact, the cement mix is very sensitive to the addition of SP. During the early hydration, the workability of concrete is more controlled by its C_3A content: soluble sulphates while the particle-size distribution, packing density and surface area control the flowability (Zingg *et al.,* 2009). The addition of superplasticiser into the mix influences the physical properties of concrete: such as the viscosity as well as the yield stress and, at higher concentration, some types of SP can lead to bleeding.

Zingg *et al.* (2009) observed that the optimisation of the superplasticiser depends on the C_3A content: an increase in C_3A content leads to higher polycarboxylate (PCE) adsorption and requires a higher PCE concentration to achieve saturation.

Some SCC problems such as segregation and bleeding can be mitigated by designing a concrete mix with the necessary viscosity, and this can be achieved in different ways such as increasing the fine aggregate content, using (VMA) viscosity modified admixtures, limiting the maximum aggregate size or increasing the powder content (Sahmaran *et al.,* 2006). Due to the cost involved in manufacturing SCC based on these said admixtures, one option of reducing the cost is to use mineral fillers such as limestone, cyclone dust powder and fly ash; these are fine materials, and can replace a certain amount of cement. These extenders/fillers can be added into the mix either before or during concrete mixing. The extenders/fillers not only increase the workability of the SCC but also increase its durability and long-term properties.

In conclusion, Sahmaran *et al.* (2006) acknowledge the fact that the workability of SCC relies on the type of SPs used; and the polycarboxylate-based SPs demonstrated better results in terms of workability achieved. One should not think that only the particle size of mineral extenders can improve the workability of concrete, but attention must be paid to the surface characteristic and spherical shape of some of the extenders/fillers: fly ash, for example, can also affect the workability. The setting time is also influenced by both the chemical admixture and mineral extenders. However, there is a disadvantage when trying to replace cement with the mineral extenders/fillers: the strength of SCC is sometimes decreased by this practice.

2.13 Properties of self-compacting concrete

The three key properties of SCC in its wet state are the passing ability, filling ability and resistance to segregation. As a result of only a few test methods being available up to 2005, the usage of SCC slowed down as it was difficult to verify mix-designs (The European guidelines for self-compacting concrete, 2005). The passing ability of SCC is defined as the ability to flow through dense reinforcement without blocking without the need for vibration and is measured by the L-Box test. The filling ability of SCC is defined as the ability to flow freely under its own self-weight and is measured by the slump flow test. SCC must be able to flow horizontally and vertically so as to fill the formwork completely irrespective of its shape. The flow of SCC is directly affected by the aggregates as it has an effect on the yield-stress of the mix. The resistance to segregation is the ability of SCC to maintain its state (homogeneity). One of the direct impacts on segregation is the size and shape of the aggregates. The parameters and classes for different applications of SCC are shown in Figure 2.4.

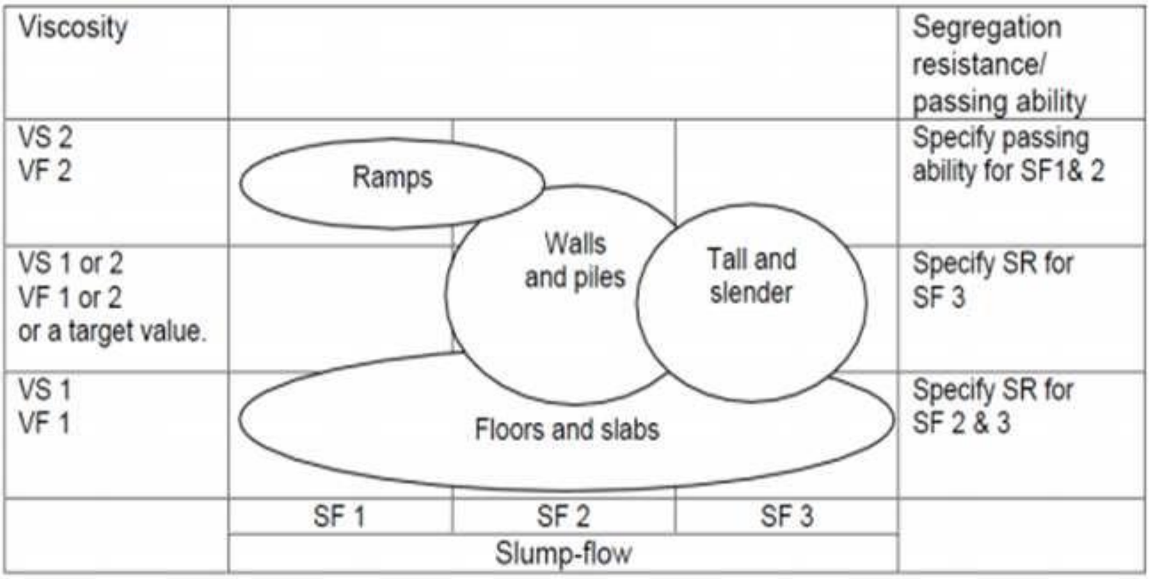


Figure 2.4: Properties of SCC for various types of applications (The European guidelines for self-compacting concrete, 2005)

2.14 Tests for Self-compacting concrete

In order to help with the understanding of SCC, a certain number of limiting values have been set as standards. However, these values have been selected arbitrarily because self-compacting concrete is still not fully understood and research is still in progress. These limits used to assess the quality of SCC are therefore subject to changes as more research is being conducted and the understanding of SCC is being improved (Koehler & Fowler, 2007). However, based on the European standard practice, the European guidelines on SCC and the European standards (EN) have also proposed classes for some of the key properties.

2.14.1 Test for filling ability: Slump flow test

The slump flow is a quick and simple test method that is the most widely used test method for SCC. The test was originally developed in Japan to measure underwater and highly flowable concrete (EFNARC, 2005).

The test is based on the regular slump cone test used to determine the slump and thus, the workability of concrete. The test indicates the SCC's horizontal unobstructed flow, and the diameter of the SCC circle is used as a measure of the SCC's filling ability. A larger spread and therefore a higher slump flow value indicates a greater filling ability (EFNARC, 2005). The basic apparatus includes a metal cone (200 mm diameter base, 100 mm diameter top, 300 mm high and 1.5 mm thick) and a flat-base plate 900x900 mm with the T_{500} diameter line engraved very clearly on it. The measurements of the base plate are illustrated in Figure 2.5.

Figure 2.5: Slump flow test (EFNARC, 2005)

The typical range of slump flow spread has been used in this project, according to European guidelines for SCC (2005); SF2 is 640–800 mm. The classes of filling ability based on slump flow spread are shown in Table 2.1.

Table 2.1: Classes of filing ability (EFNARC, 2005)

Slump flow spread	SF (mm)
SF1	550–650
SF2	660–750
SF3	760–850

The European guidelines for SCC (2005) notes the repeatability (r) and reproducibility (R) values of the slump flow and T_{500} has been determined in an inter-laboratory test with two replicates and sixteen operators from eight laboratories, and interpreted in accordance with ISO 5725:1994. Table 2.2 summarises these results.

Table 2.2: Precision of slump flow test (EFNARC, 2005)

Slump flow spread	SF (mm)	< 600	600–750	> 750
Repeatability	r (mm)	n/a	42	22
Reproducibility	R (mm)	n/a	43	28

Reproducibility (R) is a term that defines the likelihood of errors occurring during the same tests on identical materials, performed by different operators. Reproducibility is expressed as R and it is the random error of the tests.

Repeatability (r) is the ability to produce results that are consistent when completed by the same observer – with the same measuring instruments and materials; used under the same conditions, location and environment; over a short period of time for each test.

From the slump flow test, the following classification of materials has been obtained:

- SF1 550–650 mm low-filling ability: at this range which is the minimum level, the self-compaction of the mix is obtained. However, the actual minimum value depends on the individual mix-design. Generally, though, mixes with a slump flow spread of less than 600 mm is not self-compacting.
- SF2 660–750 mm: provides a good filling ability, and the mix can be used for most practical applications.
- SF3 760–850 mm high-filling ability: mixes with this value usually flow very easily with very low or zero-yield stress; rapidly; and over long distances. This range is more appropriate for casting in complex shapes or reinforced structures. Nonetheless, attention should be given to concrete within this range to ensure that passing ability and the segregation resistance is maintained, as the concrete needs to remain self-compacting and produce a homogeneous mix.

2.14.2 Test for passing ability: L-box Passing ratio PR

This test primarily gives an indication of the passing ability. However, this value correlates largely to the filling ability, as concrete with less filling ability is more likely to block. The ability of the L-box to detect blocking is much lower when the filling ability is much higher. The L-box therefore to some extent reflects both the filling and the passing abilities of the concrete. In some cases, the L-box results might indicate whether or not the mix is self-compacting.

The L-box test is used to determine the passing ability of the SCC mix and the flow – through openings between reinforcements, without segregation or blocking. The test method was designed in Japan and is based on an underwater concrete test method. There are two types of L-box testing methods created for different aggregate sizes, namely the two-bar and the three-bar test. The three-bar test, used in this project because of the use of 13mm, emulates congested reinforcement (EFNARC, 2005). The L-box is shown in Figure 2.6.

Figure 2.6: The L-box dimensions (EFNARC, 2005)

For this project the aim was to achieve an L-box value of 0.75 or larger as per class PA1. The PA1 class offers the SCC properties required for walls and piles. The L-box test method provides an indication of the passing ability characteristic of SCC. The classes of passing ability based on passing ratio are shown in Table 2.3.

Table 2.3: Classes of passing ability (EFNARC, 2005)

Passing ability	PA
PA1	≥ 0.8
PA2	> 0.8

The precision for repeatability (r) and reproducibility (R) is shown in Table 2.4.

Table 2.4: Precision of slump flow test (EFNARC 2005)

L-box	PR	≥ 0.8	> 0.8
Repeatability	r (mm)	0.11	0.13
Reproducibility	R (mm)	0.12	0.16

From experimental work, the following ranges are proposed for the passing ability on the L-box:

- PR1 ≥ 0.8 with two bars, the value of the passing ability makes mix in this range suitable for general applications with light or no reinforcement.
- PR2 > 0.8 with three bars, suitable for applications with more compact and denser reinforcements.

The minimum value for the passing ratio is usually given at 0.8. However, little evidence exists linking this value to the actual performance of SCC. Yet, PR values for most SCC tends to be around 0.9 which is safely above 0.8. Taking this into account, it has been shown that at PR values of 0.8 and below, the mix is highly likely to severely block or has an extremely low flowability, and therefore cannot be considered as self-compacting (De Schutter *et al.,* 2008).

2.14.3 Test for segregation resistance: Sieve segregation

The importance of fresh SCC segregation compared to TVC has led to a necessity of developing a new type of test. Reports from the application of the tests on site have suggested that the segregation resistance test is unlikely to be carried out on site. Therefore, this test is mainly limited to laboratory work during the development of SCC mix-designs. However, VMA can be used to enhance the segregation resistance of the mixture (Libre *et al.,* 2010). The result has proved that the effect of SP dosage is not linear and depends on the W/C ratio. The effect of VMA in cementitious mixtures is more dominant with a greater W/C ratio.

Increasing the content of limestone and fly ash can lead to a risk of segregation. The most important parameter influencing segregation has been found to be the W/C ratio (Libre et al., 2010). The sieve segregation apparatus comprises of a 300 mm diameter sieve with a 40 mm high wall; the sieve has 5 mm square openings that comply with ISO 3310-2. There is also a pan, for the sample that passes through the sieve, and a scale. The sieve segregation resistance test is shown in Figure 2.7.

The sieve segregation test is relatively simple to conduct; each test takes approximately 25 minutes to carry out. An automated version of the test exists, and though more expensive, is recommended above the manual one.

Figure 2.7: The sieve segregation resistance test (EFNARC, 2005)

Segregation resistance can be classed according to the level of the segregation index (EFNARC, 2005). The classes of segregation resistance based on segregation ratio are shown in Table 2.5.

Table 2.5: Classes of segregation resistance (EFNARC, 2005)

Segregation ratio	SR (%)
SR1	≤ 20
SR2	> 20

For this project, the aim was to achieve a sieve segregation that was equal to or less than 18%, as per class SR2: The SR2 class offers the SCC properties required for walls and piles. The sieve segregation test method confirmed whether the segregation resistance characteristic of the SCC has been achieved or not. The sieve segregation method provides an indication of the segregation resistance characteristic of SCC.

The precision for repeatability (r) and reproducibility (R) is shown in Table 2.6.

Table 2.6: Precision of the sieve segregation test (EFNARC, 2005)

SR%	≤ 20%	> 20%
Repeatability r	3.7%	10.9%
Reproducibility R	3.7%	10.9%

Based on the experimental data, segregation resistance can be classified as follows:

- SR1 ≤ 20 adequate resistance to static segregation or settlement.
- SR2 > 20 Good resistance to static segregation (settlement).

However, the original French classification for casting of vertical reinforced concrete suggested the following ranges:

- 0 < SR < 15 Satisfactory segregation resistance (stability).
- 15 < SR < 30 Segregation resistance uncertain, it requires testing to ensure the mix quality.
- 30 < SR inadequate segregation resistance, the mix is unstable to be used as SCC (Gesoglu *et al.*, 2009).

This classification also suggests a value of 5% segregation index for a high resistance to segregation and a filling ability adequate for placement as SCC. However, mixes with segregation ratio of more than 30% tend to have severe segregation and therefore a very poor stability.

2.14.4 Test for flow-rate

The flow rate is closely linked to the value of plastic viscosity of the mix. A fast-flowing mix suggests a low viscosity and is more likely to require a low or absent yield stress to prevent severe static and dynamic segregation. On the other hand, a mix with very low or slow flow rate suggests a high viscosity as it can be found in underwater SCC, which is designed to prevent wash-out but still allows for self-compaction.

Four types of tests exist for the flow rate: the slump flow, flow-time T_{500}, the J-ring flow time, the Orimet and the V-funnel tests. These tests measure both the filling ability and the flow rate. Viscosity (low or high) should be specified only in special cases such as those given in Table 2.7. It can be useful during mix development and it may be helpful to measure and record the T_{500} time while doing the slump-flow test as a way of confirming uniformity of the SCC from batch to batch. The range of the flow rate tests is given in Table 2.7.

Table 2.7: The range of the flow rate tests (EFNARC, 2005)

Segregation ratio	T_{500}
VS1	≤ 2s
VS2	≥ 2s

Table 2.8 gives the precision for the flow-rate tests.

Table 2.8: Precision of the slump flow time test (EFNARC, 2005)

Slump flow	Flow time T_{500}	< 3.5 s	3.5–6.0 s	> 6.0 s
Repeatability	r	0.66s	1.18s	n/a
Reproducibility	R	0.88s	1.18s	n/a

2.14.5 V-funnel: Flow-time (t_v)

The V-funnel test was first used in Japan and with the emergence of SCC its use spread. It is an easy test to carry out with direct results; however, it is bulky, thereby creating transport difficulties. Table 2.8 gives the precision and the different ranges of the V-funnel test.

The apparatus includes a V-shaped metal funnel as shown in Figure 2.8, which is fitted with a quick release watertight gate at the bottom. The V-funnel is supported off an independent frame (The European guidelines for self-compacting concrete, 2005).

Figure 2.8: V-funnel dimensions (EFNARC, 2005)

The classes of filling ability based on V-funnel time t_v (s) are described as viscosity classes in the European guidelines. The classes of filling ability based on flow time t_v are shown in Table 2.9.

Table 2.9: The range of the flow-rate tests (EFNARC, 2005)

Time flow	t_v
VF1	≤ 10s

For this project the aim was to achieve a V-funnel time below 10 seconds as per class VF1. The VF1 class offers the SCC properties required for walls and piles. The V-funnel test method provides the viscosity/flowability characteristic of the SCC. The precision of Repeatability (r) and reproducibility (R) is shown in Table 2.10.

Table 2.10: Precision of the V-funnel test (EFNARC, 2005)

V-funnel flow time	$t_{v(s)}$	3.0	5.0	8.0	12	15.0
Repeatability	r (s)	0.4	1.1	2.1	3.4	4.4
Reproducibility	R (s)	0.6	1.6	3.1	5.1	6.6

Based on the value from the V-funnel test, the following ranges were observed:

- VF1: $t_v \leq 10$ s indicates good filling ability and moderate to high flow rate.
- VF2: $7 \leq t_v \leq 27$ s moderate to low filling ability, low flow rate.

In a previous study done at the Cape Peninsula University of Technology, Haldenwang and Fester (2011) tested SCC for reproducibility rate, and higher values than specified by the European guidelines for SCC (2005) were obtained. However, most of the results were within the specified acceptable range for SCC classification. Haldenwang and Fester (2011) also tested SCC for reproducibility using local Western Cape materials in addition to limestone.

2.15 Compressive strength

Differences in compressive strength testing are dependent on the amount of limestone fines found in the mixture. Generally SCC requires more fines than CVC to achieve the required viscosity characteristics. As a result of using SP, SCC will have a higher compressive strength.

Nehdi *et al.* (2004) have shown that the reduction of extenders results in an increase in compressive strength. The extenders have the ability to accelerate the hydration process and as a result provide strength at an early age. Thus the use of extenders is only applicable to a point where the optimum amount is reached, as at higher replacement levels extenders will lower the compressive strength.

The incorporation of mineral fillers such as limestone also eliminates the need for viscosity-enhancing chemical admixtures. The lower water content of the concrete leads to higher compressive strength, in addition to better mechanical integrity of the structure. It is also known that some mineral fillers/extenders may improve rheological properties, increase the workability and long-term properties of concrete (Uysal and Sumer, 2011).

2.16 Conclusion

Self-compacting concrete is a novel type of concrete with many more advantages than conventional concrete; but it is very sensitive to the materials, extenders and admixtures used. In South Africa, SCC has only been used since 2002 and the amount of research published using local materials – including cements, extenders and admixtures – has been minimal. Although SCC has been used on a number of projects in South Africa, expertise is limited to large companies and specialist groups, and research on the effect of different extender types will provide more information to encourage the usage of SCC in South Africa.

SCC is more demanding than conventional concrete in its fresh state and its success is dependent on the establishment of the suitability of its reproducibility and three characteristics; namely passing ability, filling ability and resistance to segregation, which are all interlinked with each other. The requirements of an SCC mix needs to be considered when enhancing it with these properties.

Since SCC needs a superplasticiser to improve its workability and segregation resistance, the mix can be extremely sensitive to the slightest changes in proportioning or water content. OPCs partially replaced by extenders, like fly ash and slag, can provide some stabilisation to the mix and improve its fresh and hardened characteristics. SCC can be made with most aggregates, preferably well-graded and rounded aggregates and an ordinary Portland cement. The proportioning of materials in an SCC mix is important and there has to be a balance between the cement paste and the aggregates.

Most of the failure of SCC stems from the compatibility of concrete with the admixture used in SCC manufacture. These compatibilities have to deal with the interaction of chemical composition of cement that differs in mineralogy from one quarry to another, and the chemical structure of the admixture used which varies from manufacturer to manufacturer. The European standard in terms of limitations and test equipment for SCC (EFNARC, 2005) was used in this investigation as there is currently no South African standard for SCC.

CHAPTER 3

Chapter 3 Research methodology

3.1 Introduction

The aim of this work was to evaluate the effect that different PPC binders, based on their particle-size distribution as well as their chemical composition, have on an sufficient SCC base mix with two types of superplasticisers and extended with two types of fly ash and one slag type. This chapter deals with the research design and the research methodology adopted to achieve the aims and objectives set out in this research project.

3.2 Research design

A 50 MPa SCC mix was designed with a water/cement ratio of 0.45; sand and crushed aggregate content was kept constant at 923 kg/m^3 and 680 kg/m^3 respectively. Approximately, trail mixes were done to get optimisation mix by systematically increasing and decreasing the superplasticiser content in the SCC mix within the recommended guidelines as prescribed by the manufacturer of the superplasticisers. This mix-design conformed to the requirements for SCC.

For the optimisation process, all the materials except the superplasticiser and limestone were fixed. After the optimised base mix was determined, the extender types were added by replacing a percentage of the cement. Four 52.5N OPC cements manufactured at different factories by one supplier (named C1, C2, C3 and C4) and two types of a superplasticisers (SP1 and SP2) from two suppliers were used. For each cement type, the following extenders: FA1, FA2 and slag were tested at four different replacement concentrations.

3.2.1 Part 1

The optimum mixture (i.e. the mix with the desired SCC properties and compressive strength) for each type of superplasticiser was used. The dosage of the superplasticiser was varied while keeping the limestone concentration constant; and the slump flow, the V-funnel, passing ratio and sieve segregation ratio were plotted against the different dosage of superplasticiser to obtain an optimum concentration. After this, the dosage of the superplasticiser was kept constant while the concentration of cyclone was varied and in this case the slump flow and the V-funnel, passing ratio and sieve segregation ratio were plotted against different limestone concentrations to determine the optimum mix.

3.2.2 Part 2

The effect of the different types of superplasticisers, fly ashes and slag mixtures was investigated while keeping the superplasticiser and limestone concentrations constant. For each type of superplasticiser, the two types of fly ash FA1, FA2 and the slag were used respectively to replace the cement with different proportions. For the fly ash the concentrations were 10, 20, 30 and 40% and for slag it was 30, 40, 50, 60 and 70% by volume.

The following tests were conducted:

- The slump flow test (flowability)
- The V-funnel test (viscosity)
- The L-box (passing ability)
- The sieve segregation test (segregation resistance)
- The compressive strength at seven and twenty-eight days

All tests were conducted in accordance to the European standard EFNARC 2005.

3.3 Research methodology

All testing was done in the PPC laboratory in Cape Town. The laboratory was fully equipped and temperature controlled. The laboratory was temperature controlled with temperature ranging between 18 and 20°C.

3.4 Constituent materials

3.4.1 Cement

The cement types used in this project were Portland cement OPC Cem I 52.5N. These were manufactured by PPC at different factories. The Portland cement used in this research complied with EN 197-1 and are labelled as CEM I 52.5N.

Table 3.1 and Table 3.2 depict the physical and chemical properties of the cements used in this research.

Table 3.1: Physical properties of cements

Physical properties	Designation of the cement samples			
	C1	C2	C3	C4
Relative density	3.05	3.03	3.04	2.99
Specific surface (cm^2/g)	3750	3650	4250	3850
Consistency (%)	25	31	25	33
Initial set (min)	170	180	190	315
Final set (h)	3.25	3.75	3.75	6
45 mm residue (%)	11.7	0.6	3.9	1.8
90 mm residue (%)	1.1	0	0.5	0.1
212 mm residue (%)	0.2	0	0	0

Table 3.2: Chemical properties – mineralogical composition of the cement

Chemical components	Designation of the cement samples			
	C1	C2	C3	C4
SiO_2 (%)	20.8	21.5	20.9	22.3
Al_2O_3 (%)	3.8	4.1	4	4.7
Fe_2O_3 (%)	2.9	2.8	3	3.3
Mn_2O_3 (%)	0.1	0.7	0.6	0.4
TiO_2 (%)	0.2	0.3	0.3	0.5
CaO (%)	64	62.7	62.7	61.3
MgO (%)	1.2	3.3	2.9	2.6
P_2O_5 (%)	0.17	0.1	0.03	0.12
SO_3 (%)	2.33	2.47	2.81	2.95
Cl (%)	0	0	0	0
K_2O (%)	0.66	0.36	0.24	0.25
Na_2O (%)	0.34	0.19	0.15	0.18
Na_2O eq (%)	0.74	0.41	0.29	0.33
LOI (%)	4.11	1.83	2.83	1.74
Total (%)	100.5	100.3	100.5	100.2
FCaO (%)	1	1.3	0.95	1.43
Calcium Silicate (C_3S)	59.92	50.8	52.74	54.19
Larnite (C_2S)	13.99	20.43	18.76	17.95
Calcium Aluminium Oxide (C_3A)	3.95	2.75	1.84	2.63
Brownmillerite (C_4AF)	14.54	18.46	20.49	17.15
Periclase	1	2.92	2.08	2.49
Lime	0.35	0.41	0.51	0.4
Arcanite	1.37	0.78	0.31	1.34
Gypsum	1.62	2.74	2.92	1.29
Bassanite	3.28	0.63	0.35	2.58

Note: The mineralogical composition of the cement was determined by XRD Analysis with Rietveld refinement method – Topas.

3.5 Water

Potable water at room temperature was used to prepare the SCC mixes.

3.6 Admixture

Two different new generation type of superplasticisers were used in this project. The first superplasticiser SP1 is a modified vinyl polymer-based superplasticiser admixture. SP1is superior to melamine sulphonate-based or traditional aphthalene-sulphonate superplasticisers and first generation acrylic dmixtures when it comes to performance – in terms of slump retention and water reduction. The second superplasticiser (SP2) is a new generation polymer-type based on modified phosphonates. Its specially designed molecular structure gives it exceptional properties as a concrete additive (Zingg *et al.,* 2009).

Table 3.3 depicts the chemical properties of the SPs used in this research.

Table 3.3: Properties of the chemical admixtures

Characteristics	Destination of superplasticisers	
	SP1	SP2
Consistency	Liquid	Liquid
Colour	Amber	Brown-green
Density according to ISO 758 (g/cm^3)	1.07	1.05
	± 0.02	± 0.02
Dry content according to EN 480-8 (%)	26	20.3
	± 1.3	± 1
Chlorides soluble in water according to EN 480-10 (%)	< 0.1	≤ 0.1
Alkali content (Na_2O equivalent) according to EN 480-12 (%)	< 2.5	≤ 1

The molecular features of SPs were determined from their IR spectrum. As seen in Figure 3.1, the difference in these two SPs was observed based on the five zones that determine the IR spectrum. This difference is a correlation of the number of carboxyls that SPs have per centimetre.

- Zone 1 – see Figure 3.1:

The alcohol, terminal C-H and N-H bonds are classified in this zone. SP with great O-H molecules form hydrogen bonds that require less energy to be stretched. Therefore the peak will appear broader.

- Zone 2:
  The absorption by C-H bonds is determined in this zone. Carboxylic acid bond appears as a wide peak.

- Zone 3:
  The absorption of alkyne and nitrile is determined in this region.

- Zone 4:
  This zone helps identify the presence of ester, aldehyde, ketone, carbolxylicacide or amide functional group.

- Zone 5:
  Carbon-carbon bonds are determined in this zone.

There is a relationship between absorption and the number of carboxyl groups as shown in Figure 3.1. All polymers include carboxylate and polyoxyethylene groups: higher carboxyl groups on the main chain enable a fast adsorption (Felekoglu & Sarıkahya, 2008). The chemical structures for the two superplasticisers are very similar as all macromolecules are approximately the same shape.
Figure 3.1 illustrates the relationship between absorption and the number of carboxyl groups.

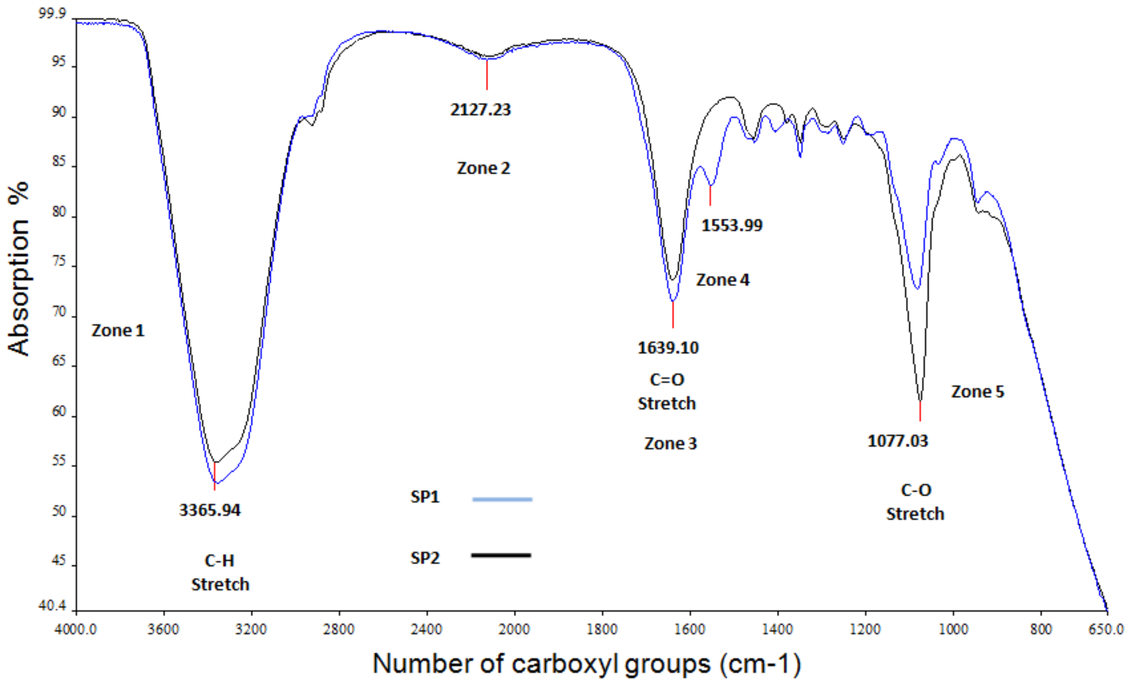


Figure 3.1: Relationship between absorption and the number of carboxyl groups

3.7 Aggregate

The aggregate used in this project was 13mm crushed stone from the Lafarge quarry in Kontermanskloof area situated in the Western Cape, South Africa. The 13 mm stone used is well-graded and has well-shaped cubical particles for optimum results in the use of SCC. The 13mm stone size was used to minimise segregation and blocking between reinforcing steel. This stone size is more freely available than 9.5 mm stone. This coarse aggregate conformed with the SANS 1083 (2006). The grading is given in Table 3.4.

Table 3.4: Sieve analysis of coarse aggregate

Sieve size (mm)	Mass retained (g)	Cumulative Passing (%)
53	0	100
37.5	0	100
26.5	0	100
19	0	100
13.2	200	89
9.5	1320	15.3
6.7	226	2.7
4.8	26	1.3
Pan	4	1.1
Total	1776	

The stone grading curve is presented in Figure 3.2.

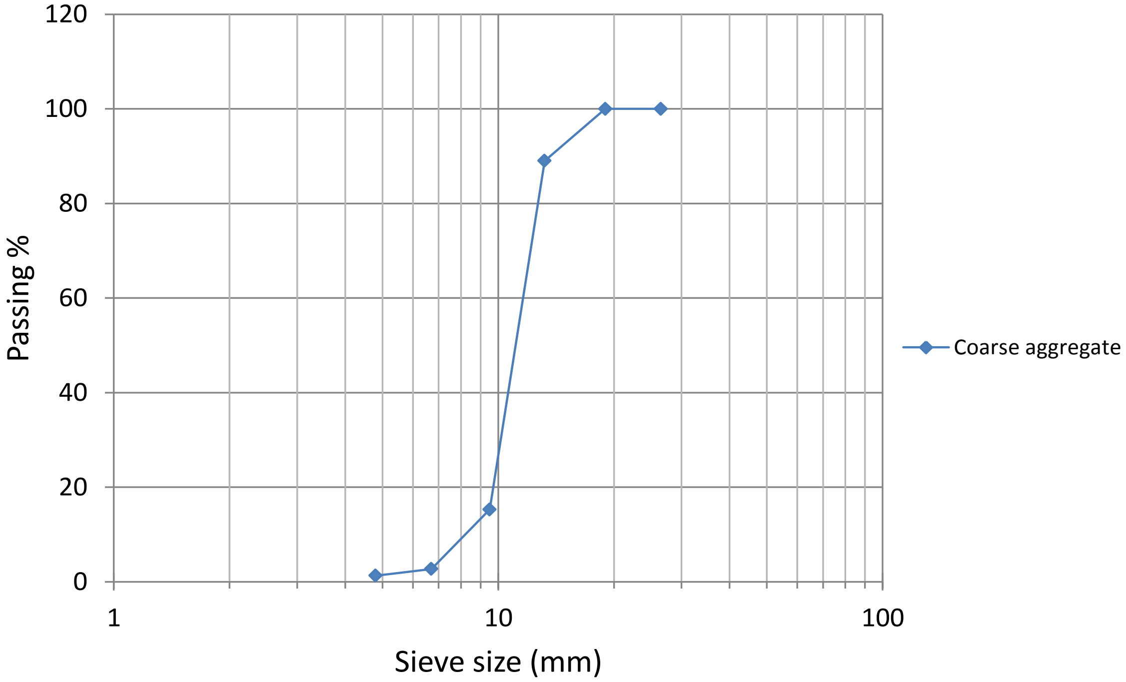


Figure 3.2: Aggregate grading curve

3.8 Sand

The sand used in this project was river sand, known as Malmesbury sand, and two batches were used. Both batches have a similar grading. This sand conformed with the SANS 1083 (2006). The properties of aggregate and sand are shown in Table 3.5.

Table 3.5: Physical properties of aggregates and sand

Properties	Coarse aggregate	Fine aggregate
	13 mm	4.75 mm
Bulk Specific Gravity (SSD Basis)	2.64	2.6
Apparent Specific Gravity	2.74	2.56
Unit Weight (kg/m^3)	1548 kg/m^3	1877 kg/m^3
Absorption (%)	1.2	1.1

The sand grading is presented in

Table 3.6 and Figure 3.3.

Table 3.6: Sieve analysis of sand

Sieve (mm)	Cumulative (%) passing sand 1	Cumulative (%) passing sand 2
4.750	99.1	100.0
2.360	90.5	97.0
1.180	68.9	79.3
0.600	47.4	56.7
0.300	33.0	37.3
0.150	17.5	19.0
0.075	10.0	9.7

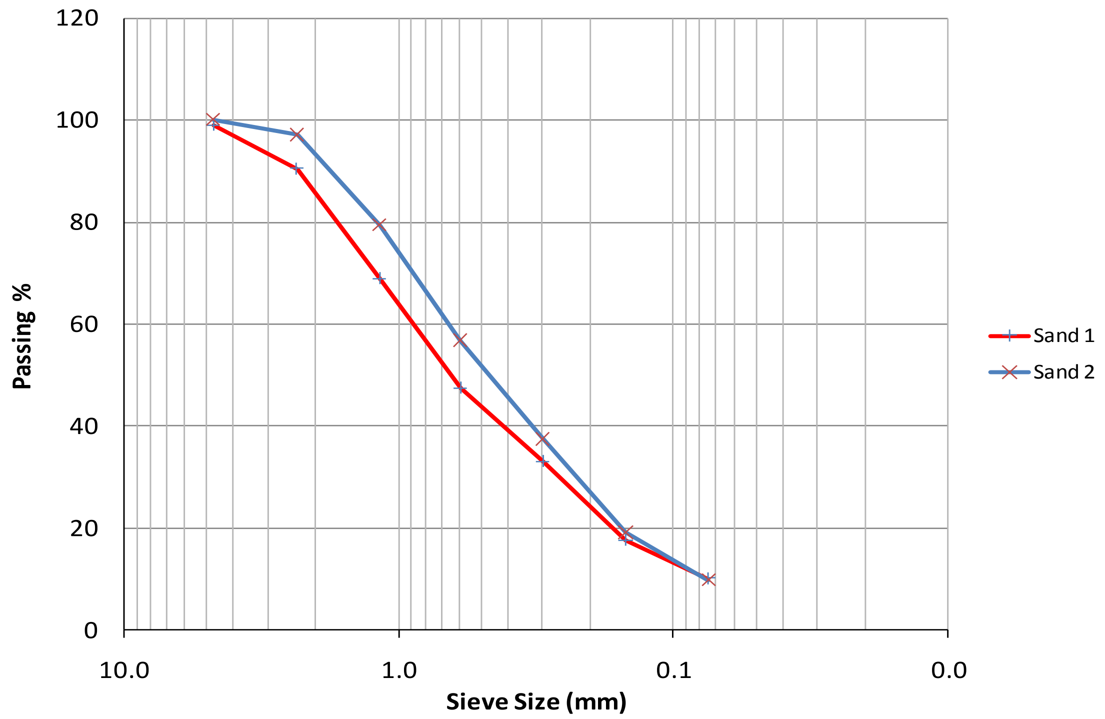


Figure 3.3: Sand grading curves

3.9 Limestone filler

Limestone was chosen as the mineral filler due to its availability in the local market and its success in the use of SCC. Sourced from Bontebok Limeworks, it is yellow in colour, although it has a finer texture. The limestone was stored in a tonne bulk bag on a plastic pallet to ensure the limestone did not become contaminated.

3.10 Fly ash

Fly Ash was chosen as an extender because of its availability in the local market. Sourced from Ash Resources, the fly ash is classified as Class F. It has low calcium content (less than 10%) and resembles cement in colour although it has a finer texture. The fly ash was stored in a 50 kg bag wrapped in plastic bags to ensure the fly ash did not become contaminated. The fly ashes used in this project were fly ash 1 (FA1) and fly ash 2 (FA2), used as partial cement replacement in cementititious products and complying with SANS 1491-2:2005. Chemical analysis of the two fly ashes is presented in Table 3.7.

Table 3.7: Chemical analysis (%) of the fly ash according to producer

Fly ash type Chemical analysis	Fly ash 1 (%)	Fly ash 2 (%)
SIO_2	53.6	53.7
AL_2O_3	27.7	33.4
Fe_2O_3	3.56	3.15
Mn_2O_3	0.07	0.06
TiO_2	1.64	1.71
Cao	7.25	4.16
MgO	1.6	0.98
P_2O_5	0.57	0.38
SO_3	0.66	0.4
CI	0.01	0
K_2O	1.02	0.77
Na_2O	0.25	0.21
LOI	1.46	0.58
Total	99.8	99.75
FcaO	-	-
IR	-	-
CI	-	-
Reactive SiO_2	33.1	37.3

3.11 Slag

The third extender type analysed was slag, produced from blast-furnace iron. The slag is ground to less than 45 microns, and has a surface area fineness of about 4000 to 6000 cm^2/kg. The slag was stored in a 50 kg bag wrapped in plastic bags to ensure that the slag did not become contaminated. The chemical analysis of the slag is presented in Table 3.8.

Table 3.8: Chemical analysis (%) of the fly ash according to producer

Slag type Chemical analysis	Slag (%)
SiO_2	33.2
Al_2O_3	14.9
Fe_2O_3	1.72
Mn_2O_3	0.05
TiO_2	0.48
CaO	35.6
MgO	11.5
P_2O_5	0.00
SO_3	2.33
Cl	0.00
K_2O	1.01
Na_2O	0.21
BaO	0.14
LOI/GOI	1.17
Total	99.9

3.12 Mix design

The mix- design used for this project is shown in Table 3.9. This mix-design conformed to the requirements well within the required parameters as found in Chapter 2 of this research for SCC. This mix design was then scaled down from one cubic metre to the 35 litres, which is the capacity of the drum mixer.

Table 3.9: Mixture proportions for 1 m^3 of SCC

Material	Relative Density	1 m^3	
		Weight (kg)	Volume
Stone	2.74	680	248
Cement	3.14	418	133
Fly ash	2	0	0
Limestone	2.72	146	54
Slag	2.9	0	0
Sand	2.56	952	372
Water	1	188	188
SP	1.08	5.64	5.22
	Total	2389	1000

3.13 Optimisation procedure

For the optimisation process, all the materials except the superplasticiser and limestone were fixed. For optimisation, just four tests were chosen as sufficient enough to determine whether the mix falls within the boundaries of SCC – as stipulated in the European guidelines for SCC (2005). The tests used were the slump flow, the T_{500}, Tf and segregation ratio. The aim of the slump flow was to get a flow spread, without visible segregation or bleeding, of 640 mm to 800 mm as to be classified as an SF2 SCC according to the European guidelines for SCC. The T_{500} time assisted in determining whether a mix was too stiff to be used as an SCC. The lowest concentration of SP was chosen as a starting point, to establish how much superplasticiser needed to be added. Gradually moving up, from this low value, the SCC was then optimised to determine which superplasticiser content would work best. After the sufficient base mix was determined, the extender types were added by replacing a percentage of the cement.

3.14 Experimental procedures

Initially a 25-litre mix was used for the optimisation of the superplasticiser and the limestone. The mix amount was then increased to a 35-litre mix, which was used to determine the effect of the fly ash and slag (Approximately 10 litres more concrete was used to include the L-box test). Four testing methods as set out in section 3.15 were conducted. All materials used were weighed on a calibrated scale before being mixed in the drum mixer. All the materials were placed in the mixer – starting with the stone, fine materials and sand on top. The mixer was started and the water and superplasticiser were added. The mixing time took 4–6 minutes. About six litres of concrete was used to do the slump-flow test. Six litres of concrete was used to prepare six test cubes (100 mm x 100 mm x 100 mm). The cubes were labelled and stored in a tank at constant temperature. Three cubes were tested after seven days and the remaining three after twenty-eight days. Approximately eight litres of concrete was used to do the V-funnel test and ten litres for the L-box test. About five litres of concrete was used to do the sieve segregation test.

3.15 Testing

The tests used for determining the properties of each SCC mixed batch are described in detail in this section.

3.15.1 The slump flow test

The slump flow indicates the filling ability of SCC, and measures two restrictions of SCC; namely flow spread and flow time (De Shutter 2005). Included in this test is the T_{500} value which can be related to viscosity. A conventional slump cone is used in this test (measuring 100 mm in diameter at the top and 200 mm in diameter at the bottom; with a height of 300 mm; and 1.5 mm thick). The test is performed on a 900 mm x 900 mm base plate with a 500 mm diameter drawn on the surface for the measurement of the T_{500} time.

Testing procedure:

- Place the clean base plate on a level and clean surface; ensure the plate is level using a spirit level.
- During the one minute waiting period, wipe the inside of the cone and the surface of the base plate with the damp cloth, ensuring that the surfaces are neither too wet nor too dry.
- Make sure that the cone is completely filled with the fresh concrete and allowed to stand for no longer than 30 seconds.
- No rodding, vibration or any other methods are used to disturb the mixture.
- The cone is vertically lifted in one uniform movement without any interference to the flow of the sample. The T_{500} time is recorded by starting the stopwatch the moment the cone is lifted from the base plate, and stopping the stopwatch the moment the concrete reaches any point on the 500 mm diameter circle engraved on the base plate.
- Time to the nearest 0.1 second must be measured and recorded.
- The slump cone can be fitted with a concrete collar of at least 9 kg to keep the cone in place when filling it with concrete.
- This allows the filling process to be done by only one person.
- The cone can also be fitted with foot rests to stand on when filling the slump cone.

- The maximum and minimum perpendicular slump diameters d1 and d2 are to be measured, from which the average is to be calculated and represented as the flow spread.

Figure 3.4 illustrates the dimensions of the equipment used for the slump flow test.

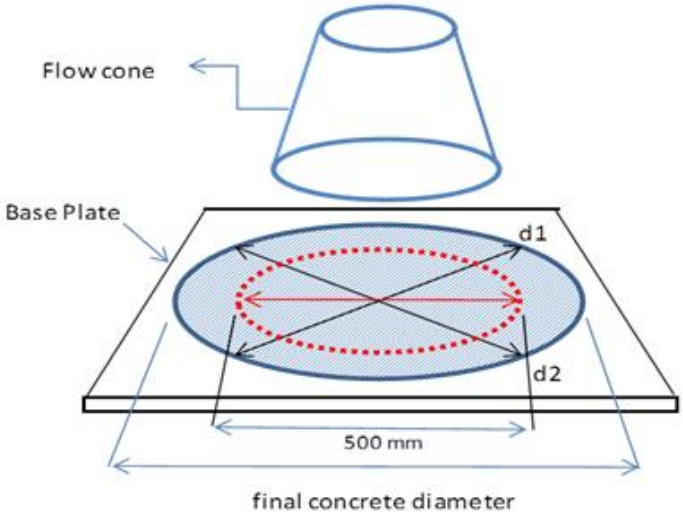


Figure 3.4: Slump flow test (EFNARC, 2005)

3.15.2 The V-funnel test

V-shaped funnel is filled with fresh concrete and the time taken for the concrete to flow out of the funnel is measured and recorded as the V-funnel flow time. The test indicates the flow ability as well as the viscosity of the SCC. (De Schutter, 2005).

Test procedure:

- Dampen the interior of the V-funnel and place on a level surface with the gate closed and a container placed underneath the opening.
- Fill the V-funnel continuously with SCC to the top, without compacting the concrete.
- Wait one minute for the concrete to settle and observe for segregation and bleeding.
- Open the gate and start stopwatch simultaneously.
- Record the time when the concrete flows out of the V-funnel (flow time = Tf)
- If blocking occurs, it indicates instability of the SCC mix.
- This time is recorded as time flow.

Figure 3.5 shows the dimensions of the equipment used for the V-funnel test.

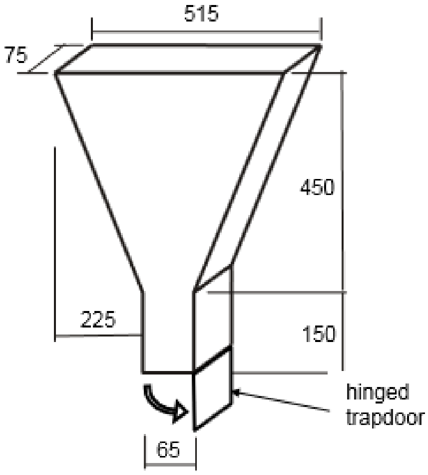


Figure 3.5: V-funnel test apparatus (EFNARC, 2005)

3.15.3 The L-box test

The L-box test is based on the L-flow test developed in Japan for underwater concrete. The L-box test is performed to determine the SCC's passing ability. The height of SCC, after passing through the spaced steel bars and within a specified flow distance, indicates the passing or blocking behaviour of the SCC. The L-shaped box as shown in Figure 3.6 is 700 mm long and 600 mm high, with three reinforcing bars 12 mm in diameter placed in front of the gate.

Testing procedure:

- Clean and dampen the interior of the L-box and place on a level surface with the gate closed.
- Fill the vertical section of the L-box continuously with SCC to the top, without compacting the concrete.
- Let the SCC stand in the vertical part for one minute (±10 sec), during which time the SCC will indicate whether it is stable or not with regard to segregation.
- In one movement, lift the gate of the L-box vertically as to allow the SCC to flow from the vertical part; through the steel bars; and into the horizontal part of the L-box.
- Measure the H1 and H2 distance as soon as the concrete stops flowing.
- The passing ratio of H2/H1 should be between 0.8 and 1.0.

Figure 3.6 depicts the equipment used for the L-box test.

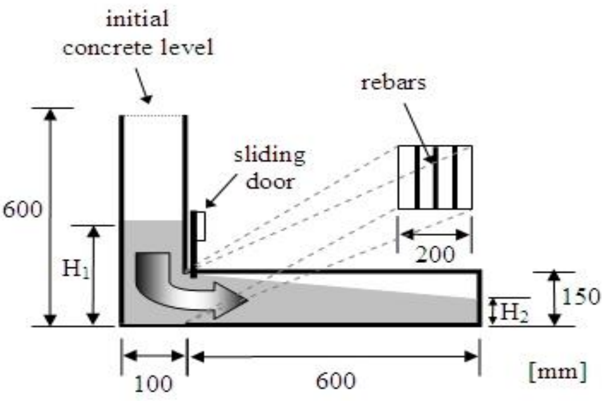


Figure 3.6: L-box test (EFNARC, 2005)

3.15.4 The segregation resistance test

The resistance of SCC to segregate can be identified by determining what portion of an SCC sample passes through a 5mm sieve. When the paste of SCC passes easily through the sieve then it is an indication of poor resistance to segregation (De Schutter, 2005).

Test procedure:

- Clean and dampen the interior of the sieve of a 300 mm with a 40 mm-high wall.
- Fill the sieve continuously from a height of 500 mm above the sieve with SCC, without compacting the concrete.
- Wait two minutes for the concrete to settle and observe for segregation and bleeding.
- The weight of the pan and sample is recorded.
- To determine the percentage segregation ratio, the weight of the pan is subtracted from the weight of the pan and sample remaining in the pan.
- This is divided by the weight of the sample originally poured on the sieve and expressed as a percentage.

Figure 3.7 illustrates the specifications of the equipment used for the segregation test.

Figure 3.7: Sieve segregation equipment (EFNARC, 2005)

3.16 Compressive strength

Test moulds were 100 mm x 100 mm x 100 mm and were well-cleaned and oiled before each use. The concrete cubes were carefully removed from the moulds after two days, with the aid of an air compressor. All the cubes were clearly marked and recorded in a log book to ensure the correct amount of curing days before the compressive test. The cubes were cured underwater in a temperature-controlled water bath. For all the mixes, six cubes were cast; three were compressive tested at seven days; and the other three at twenty-eight days. The average of the three compressive tests was determined and recorded. The mix was designed to achieve 50 MPa at twenty-eight days. The cube-crushing machine is shown in Figure 3.8.

Figure 3.8: Cube-crushing machine

3.17 Scope of work

The objectives of this project were to investigate the effect of four different cements optimised with two types of superplasticisers and limestone. All the data obtained in the SCC testing was compared with the criteria as set out in the European guidelines (2005). The passing ability was determined by means of the L-box test and the viscosity and flow ability by means of the slump-flow and V-funnel tests. The segregation resistance was determined by the sieve segregation test and the strength by means of compressive testing. Data from each test was recorded on data sheets and compared. Line graphs were compiled to determine the amount of superplasticiser and limestone required to achieve a sufficient base mix.

After optimisation, replacements of two fly ashes (FA1, FA2) and one type of slag were carried out. For each cement-type, five tests pertaining to the SCC properties were conducted in this sequence: The optimisation of SP and limestone consisted of thirteen mixes for each SP (nine mixes for SP optimisation and four for limestone optimisation). The replacement of extenders (FA1, FA2 and slag) for each SP was ensured. Thereafter the graphs were compiled to illustrate the effect of the different extender types.

The compressive strength was measured after seven and twenty-eight days for each mix. A test plan of the experimental scope is depicted in Figure 3.9. In total, 1 248 tests were conducted.

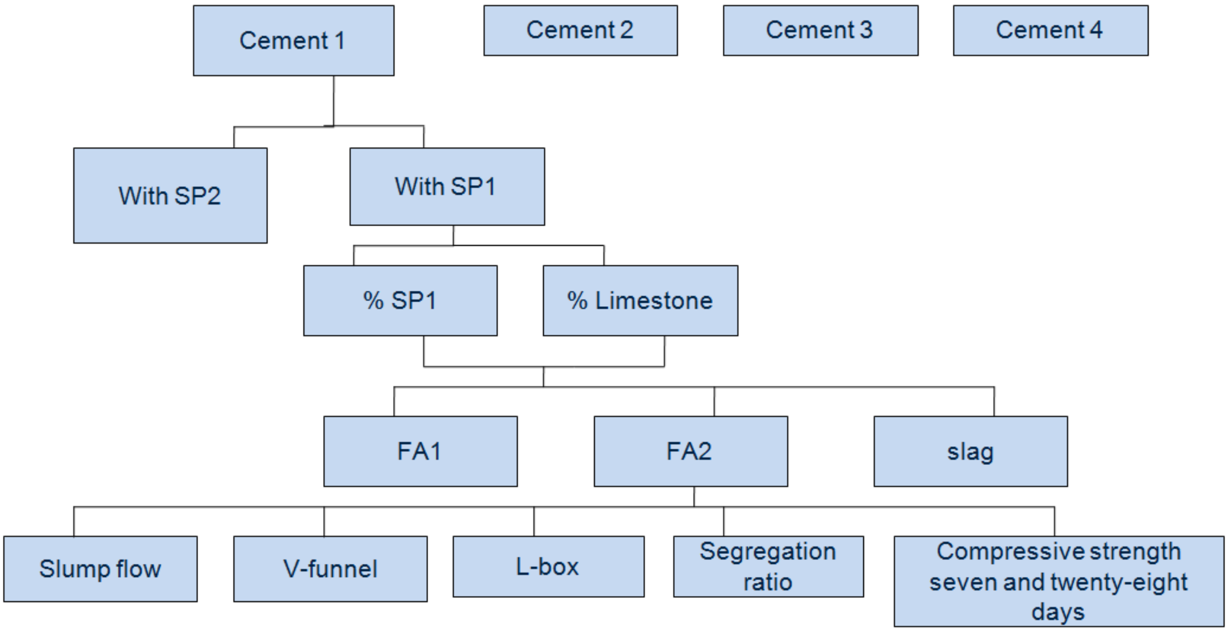


Figure 3.9: Experimental test plan

3.18 Analysis and preparation of results

All the data obtained in the SCC testing was compared with the criteria as set out in the European guidelines (2005). The passing ability was determined by means of the L-box test, and the viscosity and filling ability by means of the slump flow and V-funnel testing. The segregation resistance was determined by the sieve segregation test and the strength by means of compressive testing. Data from each test was recorded on data sheets and compared. Line graphs were compiled to determine the amount of superplasticiser and limestone required to achieve an optimised base mix. Thereafter, the graphs were compiled to illustrate the effect of the different extender types.

The determination of the chemical and physical characteristics of cements that offered a great SCC with required properties, related to flowability; resistance to segregation; and compressive strength was done as follows: Since the workability of SCC depends strongly on the mineralogy and physical features of cements, it was important to determine in which range these cement characteristic could be defined so that when replaced, the cement with different extenders in the presence of both SP1 and SP2, the set properties of SCC could all be met.

Therefore the effect of each extender (different level of extending) on individual properties (slump flow, segregation ratio and target-compressive strength) of SCC was monitored by observing the variation of the said properties with variations of cement chemistry such as the compounds (C_3A, C_3S and Na_2Oeq) of cements as well as the surface area.

CHAPTER 4

Chapter 4 Results

4.1 Introduction

This chapter presents the results obtained during the experimental testing. Four CEM I 52.5N cements produced at different PPC factories were used. The first set of results deals with the optimisation of the superplasticiser and limestone volume. Thereafter, the effect of the extender types: the two types of fly ash – FA1 and FA2 -- and slag are presented. The same testing methods were applied for all the extender types. The results for each testing method were combined and presented graphically.

4.2 Conformity to SCC standards

Since the superplasticiser content and limestone used needed optimisation, all other quantities were kept constant. Since the relative densities of cements and extenders (fly ash and slag) are different this was taken into account when calculating the masses in order to keep the mass per 1 m^3 of concrete constant which meant that the sand content increased when the cement was replaced. Table 4.1 shows how well the mix design conforms to what is prescribed by the European guidelines for SCC (2005).

Table 4.1: European guidelines for SCC (2005) mix composition range compared to 50MPa SCC mix used in this research

European Standards - SCC classification			50 MPa SCC mix design	
Constituent	Typical range by mass kg/m^3	Typical range by volume litre/m^3	Typical range by mass kg/m^3	Typical range by volume litre/m^3
Powder	380-600		564	
Paste		300-380		380
Water	150-210	150-210	188	188
Coarse aggregate	750-1000	270-360	680	248
Fine aggregate(sand)	48-55% of aggregate weight		45.95%	
Water/Powder ratio by volume		0.85-1.10		1.01

4.2.1 Aggregate grading

A change in grading of the aggregate can lead to a considerable change in SCC quality and this can therefore influence the test results. The coarse aggregate in the mix design used for this project was a 13 mm, Hornfells stone which was sourced from a local quarry (Lafarge Quarry). Research started with finding the sufficient amount of aggregate to successfully design a mix that would conform to all the prerequisite limits. Many trail mixes were attempted to stay within the EFNARC 2005 limits but that did not result in an acceptable SCC, so the amount of the aggregate was reduced in order to avoid segregation. The sieve analysis can be found in chapter 3 at Table 3.4 while Figure 3.2 shows the aggregate sieve analysis of the SCC mix.

4.2.2 Sand grading

The grading analysis for the sand used in this project can be found in Table 3.6 and Figure 3.3 in chapter 3. This was the average grading analysis throughout the project. All the experimental testing was conducted by using one heap/delivery of sand to ensure uniformity. Grading of sand or particle size distribution is important in any concrete design approach and plays an even more important role in Self Compacting Concrete.

4.3 Optimisation of base Mix

To determine the optimum base mix, it is necessary to determine the optimum volume of superplasticisers – SP1 and SP2 – and limestone volume. Table 4.2 shows the sufficient mix design used for this research.

Table 4.2: Sufficient SCC mix design

50 MPa SCC mix design			
Material	Relative density	1000 litre	
		Weight (kg)	Volume
Aggregate	2.74	680	248
Cement	3.14	418	133
Limestone	2.72	146	54
Sand	2.56	952	372
Water	1	188	188
SP	1	5.64	5.22
	Total	2390	1000

One control and many mixes with mineral admixtures were prepared and examined to quantify the properties of SCC.

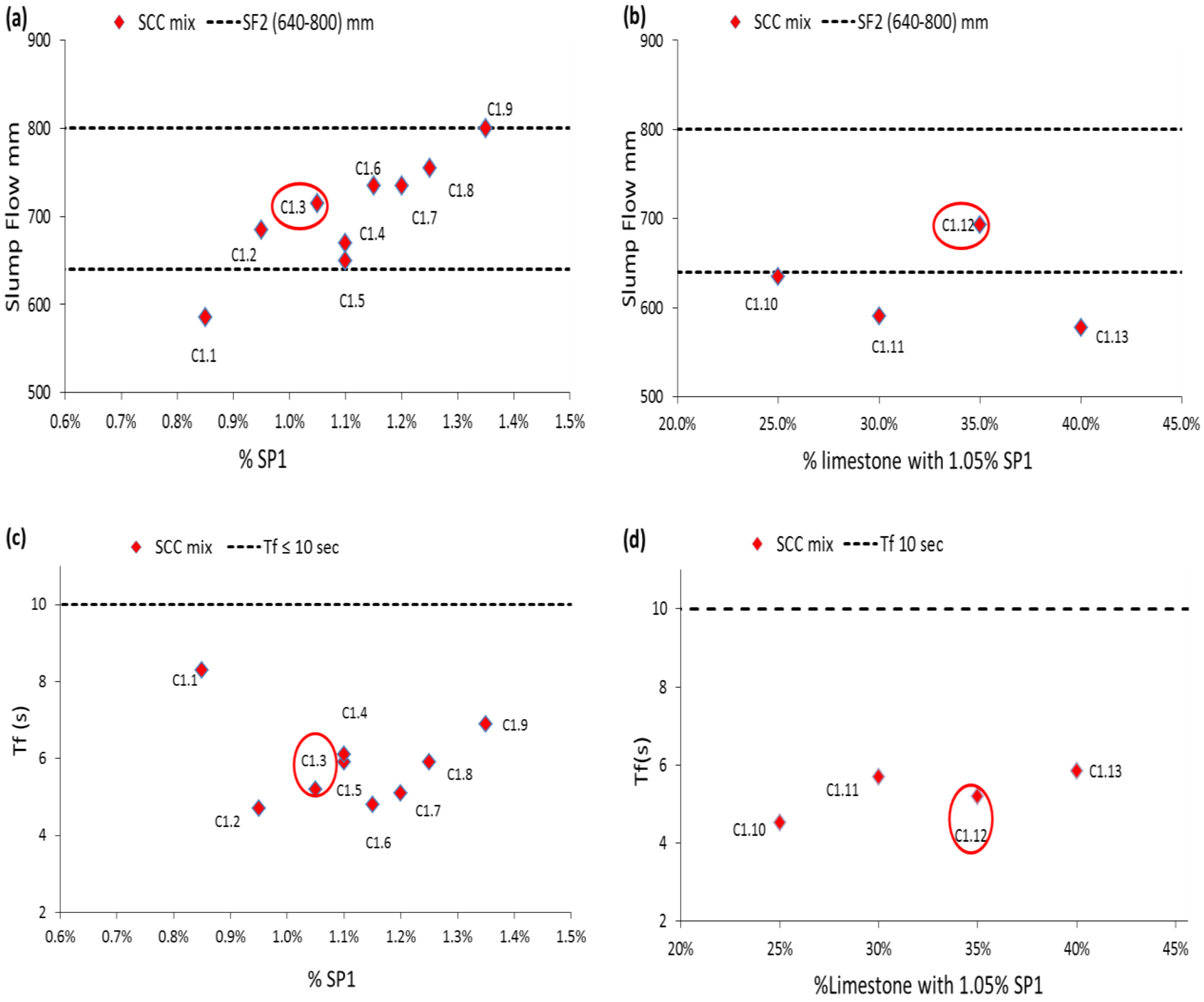
Table 4.2 shows the sufficient mix design used for SCC mix for 1000 litres and 35 litres. For each cement type, cement was replaced with FA1, FA2 and slag at the same contents of 10%, 20%, 30% and 40% respectively; and 30%, 40%, 50%, 60% and 70% for slag. After some preliminary investigations, the water–cement mass ratio W/C was selected as 0.45; and the cement content was fixed at 418kg/m3.

4.3.1 Superplasticisers

For the optimisation of the superplasticiser, the volume of all materials – except the volume of the superplasticiser – was kept constant. Testing was done until the lower and upper limit of the superplasticiser volume could be determined. The superplasticiser was expressed as a percentage relative to the weight of the fines. The fines include all particles in the mixture passing through the 0.125 mm sieve including some of the sand, cement and limestone. For this project the percentage of the superplasticiser was determined by the fines as set out above section excluding the fines of the sand. For the optimisation of the superplasticiser, 35% limestone was used. Figure 4.1 (a) displays the slump flow results for cement C1 relative to the percentage of the superplasticiser SP1. The middle of the stipulated recommended range, as given by the manufacturer, was chosen as a starting point for the SP dosage. Gradually moving up and down from this value, the SCC was then optimised to determine which superplasticiser concentration would be the best. The lowest percentage of superplasticiser used was 0.85% as seen in test C1.1; the result was below the SF2 specified limit of 640 mm as set out in the European guidelines. The highest percentage of superplasticiser used was 1.35% as seen in test C1.9; this was for SF2 at the specified limit of 800 mm. Figure 4.1 (c) displays the V-funnel results. All of the V-funnel results were within the 10-second specified limit except test C1.1, achieving a slump flow measurement of 585 mm. Figure 4.1 (e) displays the sieve segregation results relative to the percentage superplasticiser SP1 used. C1.3 at 1.05% SP1 concentration was chosen as the most suitable mix since it is optimally located at the middle of the slump-flow range.

According to the European standard, the segregation should be below 18%. From the results obtained it is evident that none of the tests were within the required specification except C1.12 with 35% limestone, as can be seen in Figure 4.1 (b). For each mix, six compressive tests were done – three at seven and three at twenty-eight days. The mix was designed to achieve 50 MPa at twenty-eight days.

The 1.05% dosage delivered a very homogeneous and coherent mix. Once the slump flow spread also fell within the SF2 category, there were no signs of segregation as an even layer of stone and paste distribution was visible with no bleeding around the edges of the SCC slump. From the results obtained during testing, the decision was made to use 1.05% superplasticiser (SP1).


(a)
SCC mix
SF2 (640-800) mm
Slump Flow mm
900
800
700
600
500
C1.1
C1.2
C1.3
C1.4
C1.5
C1.6
C1.7
C1.8
C1.9
0.6%
0.7%
0.8%
0.9%
1.0%
1.1%
1.2%
1.3%
1.4%
1.5%
% SP1
(b)
SCC mix
SF2 (640-800) mm
Slump Flow mm
900
800
700
600
500
C1.10
C1.11
C1.12
C1.13
20.0%
25.0%
30.0%
35.0%
40.0%
45.0%
% limestone with 1.05% SP1
(c)
SCC mix
Tf ≤ 10 sec
Tf (s)
10
8
6
4
2
C1.1
C1.2
C1.3
C1.4
C1.5
C1.6
C1.7
C1.8
C1.9
0.6%
0.7%
0.8%
0.9%
1.0%
1.1%
1.2%
1.3%
1.4%
1.5%
% SP1
(d)
SCC mix
Tf 10 sec
Tf(s)
10
8
6
4
2
C1.10
C1.11
C1.12
C1.13
20%
25%
30%
35%
40%
45%
%Limestone with 1.05% SP1

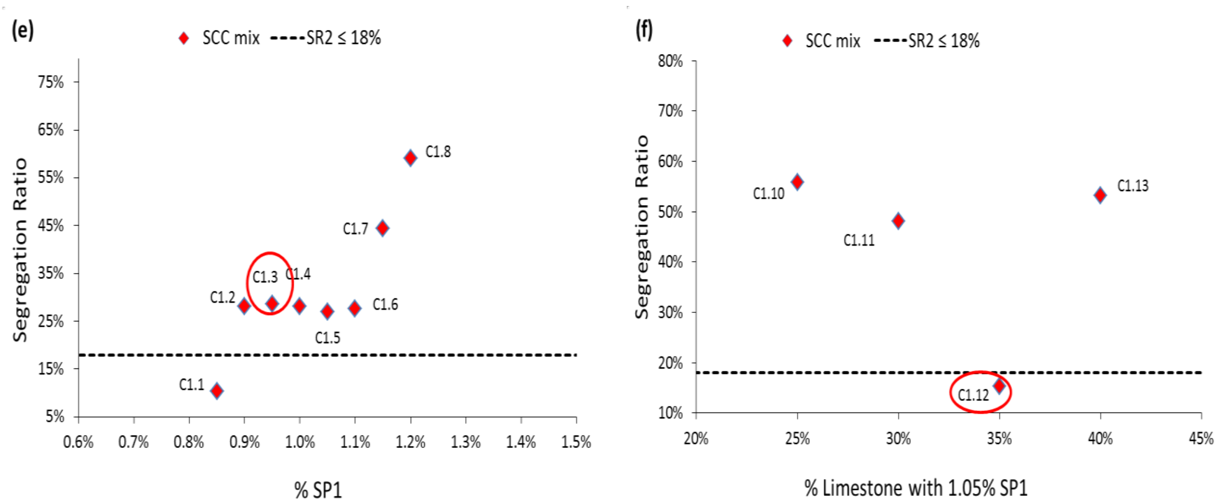


Figure 4.1: SCC test results for C1 relative to SP1 percentage and limestone

4.3.2 Limestone

The optimisation of the limestone was done after the optimisation of the superplasticiser. The volume of all materials except the volume of the limestone and sand were kept constant during the optimisation. The volume of the limestone is expressed as a percentage of the cementitious material. Testing was done with 25%, 30%, 35% and 40% limestone.

Figure 4.1 (b) illustrates the slump flow results relative to the percentage limestone used for cement C1. Most of the testing did not meet the required slump flow as specified in the European specification except mix number C1.12, achieving a slump of 690 mm. Figure 4.1 (d) displays the V-funnel results. All of the V-funnel results were below the ten second restriction as set out in the European specification. Figure 4.1 (f) displays the sieve segregation results relative to the percentage limestone used. According to the European standard the segregation should be below 18%. From the results obtained it is evident that only tests C1.12 with 35% limestone was within the required specification. From the results obtained during testing the decision was made to use 35% limestone.

The above optimisation procedure was also conducted for the other three cements C2, C3 and C4 used in this study, including the two different types of superplasticiser. The resulting graphs and data are illustrated in the Appendices (B, C, D, E, F, J, and K).

4.4 Effect of different superplasticisers on different cement types

In accordance with the European standard, SCC requires a slump flow between 640 mm and 840 mm to be within the SF2 category. From Figure 4.2 (a) in terms of slump flow, all sufficient SCC mixes exhibited satisfactory slump flow, which were between 640 mm and 800 mm as recommended by (EFNARC, 2005). There is no clear difference in the results for the four cements. The results of the T_{500} and Tf parameters for the different cements and superplasticisers are illustrated in Figures 4.1 (b) and (c). As can be seen in Figures 4.1 (b) and (c), the test results showed that the T_{500} parameter was higher for all four cements when mixed with SP1 compared to mixes with SP2. Moreover, theT_{500} parameters were less than five seconds in accordance to EFNARC (2005), for all mixes.

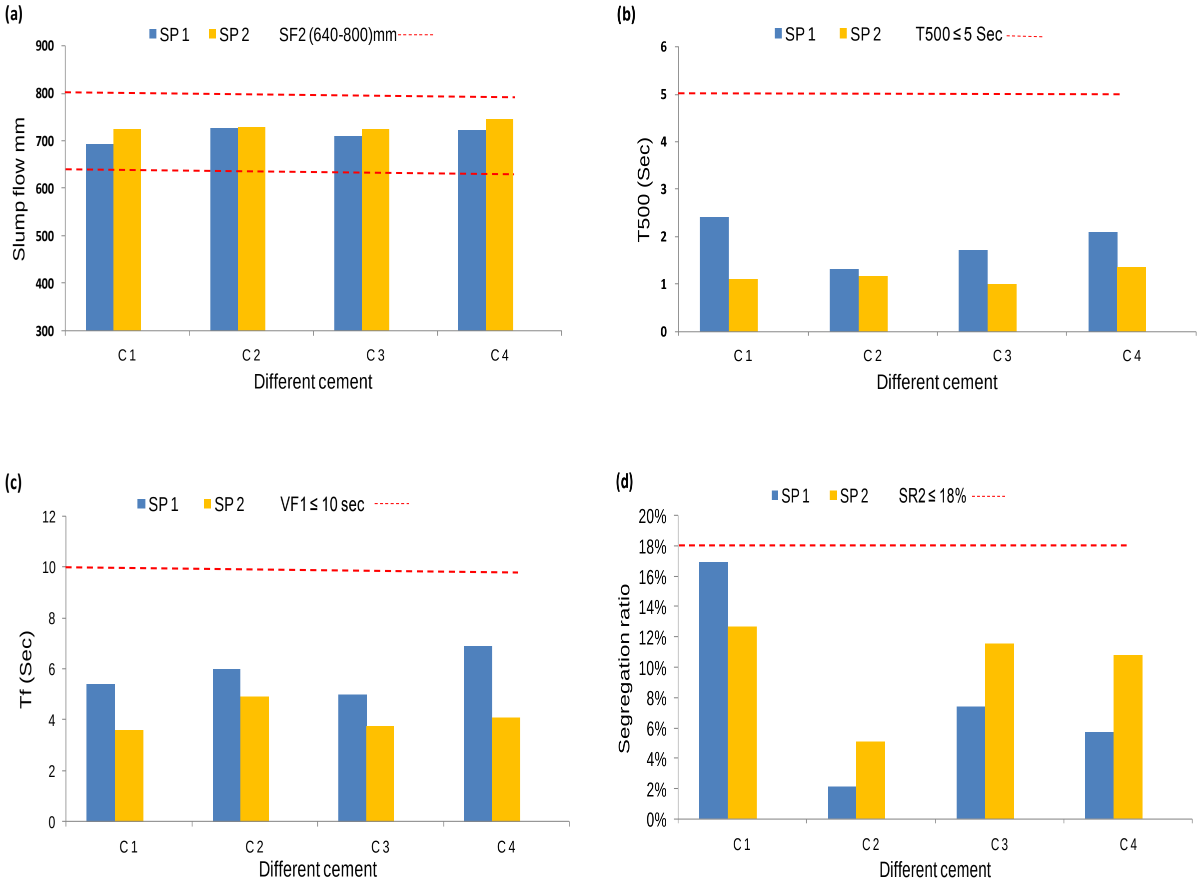


Figure 4.2: Effect of different SPs on different cements

Similarly to T_{500}, the plastic viscosity represented by the Tf parameter, increased with SP1 for different cements compared to cement mixes with SP2. The V-funnel flow times ranged below ten seconds, in accordance with EFNARC (2005) which recommends that Tf be less than ten seconds for designing appropriate SCC mixes, as presented in Figure 4.2 (c).

Segregation tests were also conducted and the results for the tests are presented in Figure 4.2 (d). In terms of segregation resistance, all sufficient SCC mixes exhibited satisfactory segregation ratios which were less than 18% as recommended by EFNARC, 2005, which states that for design purposes the upper limit of the segregation ratio (SR2) should be less than 18%. However, an anomaly was observed with the SP1 and C1 mix which yielded a higher segregation ratio than other cements with SP1. Altogether SP1 mixes were more satisfactory for cements C2, C3 and C4 compared to those with SP2.

4.5 Effect of limestone addition on different cement, using different SPs

The optimisation of the limestone was done after the optimisation of the superplasticiser. The volume of all materials, except the volume of the limestone and sand, were kept constant during the optimisation. The volume of the limestone is expressed as a percentage of the cementitious material. Testing was done with 25%, 30%, 35% and 40% limestone composite. Figure 4.3 illustrates the results obtained from using different limestone proportions for different cements with different SPs.

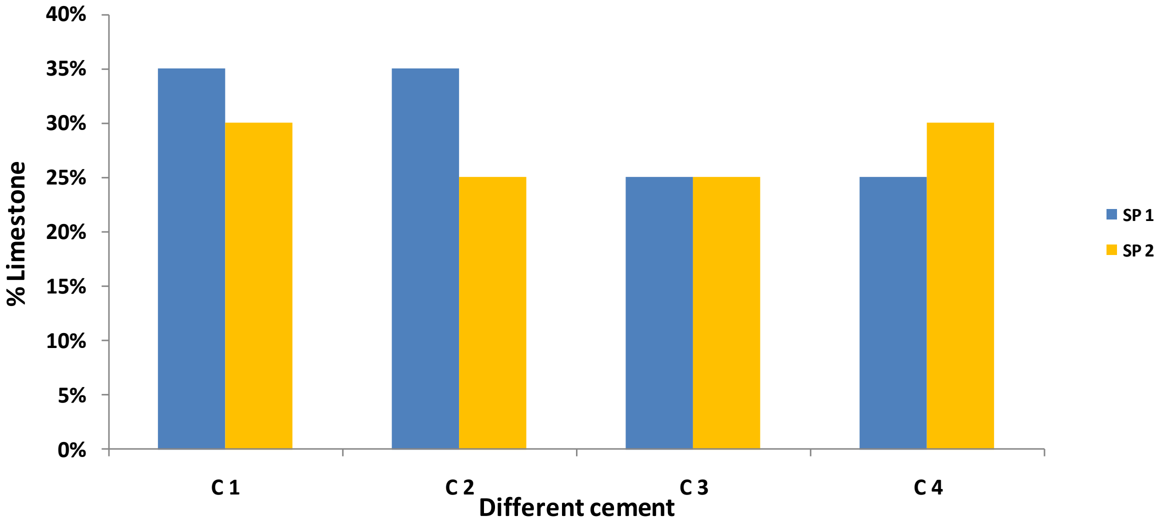


Figure 4.3: Optimised limestone proportion for different cements with different SPs

Most of the testing met the required slump flow and segregation ratio as recommended in the European specification. As previously stated, tests started off with lower compositions of limestone, and increased up to 40%. The test results revealed that C1 and C2 with SP1 required more limestone addition compared to other cement mixes using the same superplasticiser. Overall, when comparing SP1 and SP2 mixes, SP1 mixes required more limestone addition. An exception was the case with C4 and SP2 which had a higher value than SP1 with the same cement. As for C3, both superplasticisers had the same limestone requirement.

4.6 Effect of limestone addition on compressive strength, using different SPs

The results of tests on compressive strength at twenty-eight days for different cements with SP1 and SP2 are presented in Figure 4.4: (a) and (b). It is evident in Figure 4.4 (a), with SP1 that all of the cements achieved more than 50 MPa at twenty-eight days with different limestone proportions 25%, 30%, 35% and 40% except for C3 at 35% and 40 %. C2 achieved the highest average strength at 25% limestone.

From Figure 4.4 (b), with SP2, it is evident that all of the cements achieved more than 50 MPa at twenty-eight days with different limestone proportions 25%, 30%, 35% and 40%. C4 achieved the highest average strength at 35% limestone content.

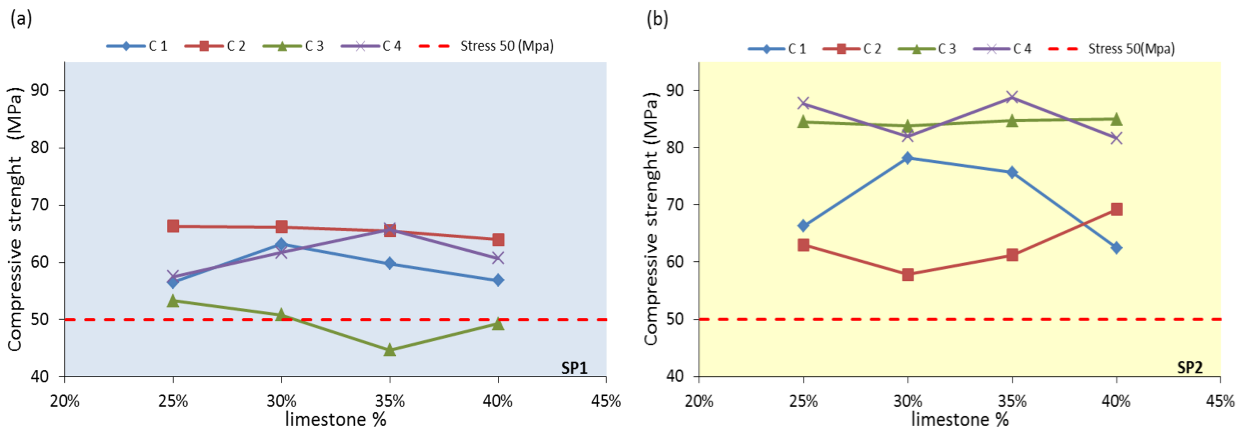


Figure 4.4: The effect of limestone addition on compressive strength, using SP1 and SP2 on different cements

4.7 Effect of different superplasticisers on slump flow/time flow

In accordance with the European standard, SCC requires a slump flow between 640 mm and 840 mm to be within the SF2 category. The sufficient mixture without any extender types achieved a slump flow between 640 mm and 800 mm and the Tf less than ten seconds.

4.7.1 Effect of SP1 on slump flow/time flow

For the different cements, the lowest dosage of superplasticiser required to maintain good filling ability for C2 was 1.0%, whilst for C4 it was 1.2%. The sufficient superplasticiser dosage was kept constant for all the mixes before the fly ash and slag replacements. Figure 4.5 illustrates the slump flow results relative to time flow (V-funnel) for SP1. Most of the testing met the required slump flow as specified in the European specification of 2005. All concrete mixes in the presence of SP1, had a slump flow in the range of 700 mm to 750 mm, with flow time less than five seconds.

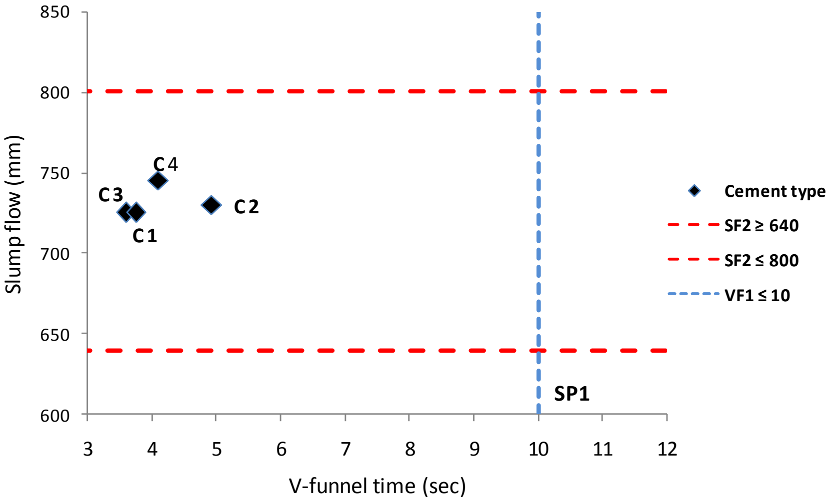


Figure 4.5 Slump flow results relative to V-funnel results, using SP1

As for the V-funnel tests with SP1, all results were well within the upper limit suggested by EFNARC (2005). C3 achieved the lowest V-funnel time in comparison to the rest of the cements. C4 had the highest V-funnel time which means the highest plastic viscosity.

4.7.2 Effect of SP2 on slump flow/flow time

For different cements as can be seen in Figure 4.6, the lowest dosage of superplasticiser required to maintain good filling ability was 2.8% for C4 , while a higher dosage of superplasticiser of 3.4% was required to maintain a good filing ability for C2. All cements met the EFNARC (2005) requirements, with a slump flow ranging between 670 mm and 730 mm within less than second seconds of flow time.

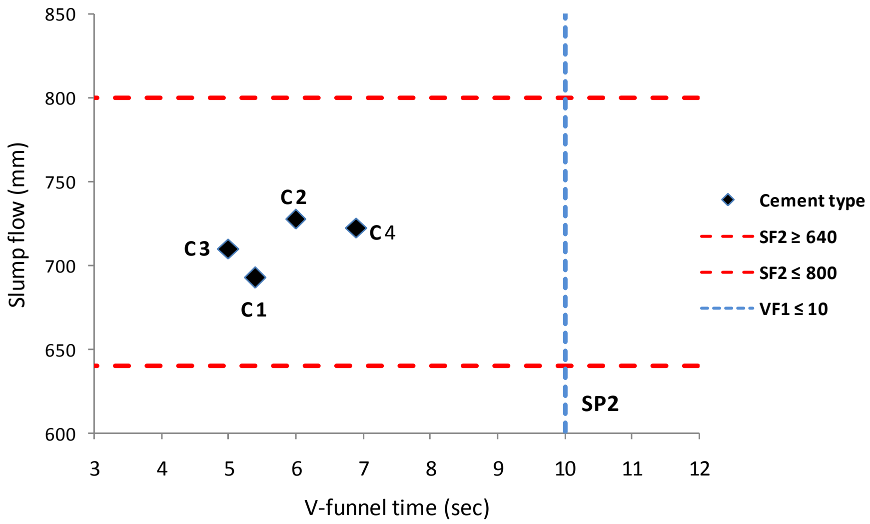


Figure 4.6 Slump flow results relative to V-funnel results, using SP2

As for the V-funnel tests with SP2, all results were well within the upper limit suggested by the EFNARC (2005). C3 achieved the lowest V-funnel time in comparison to the rest of the cements. C2 had the highest V-funnel time, which means that it had the highest plastic viscosity.

4.8 Effect of different superplasticisers on slump flow/segregation resistance

In accordance with the European standard, SCC should achieve less than 18% segregation. The sieve stability test investigates the resistance to segregation of SCC, showing whether an SCC mix is stable.

4.8.1 Effect of SP1 on slump flow/segregation ability

From Figure 4.7, C2 achieved the lowest segregation of 2.1% and C1 the highest segregation ratio of 17.6%.

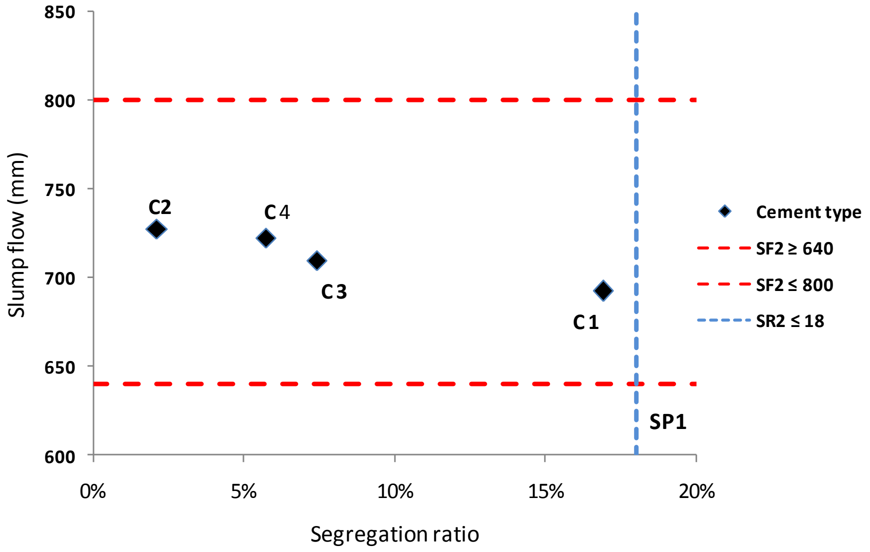


Figure 4.7 Slump flow results relative to segregation ratio results, using SP1

4.8.2 Effect of SP2 on slump flow/segregation ability

As can be seen in Figure 4.8, C2 achieved the lowest segregation ratio of 4.8%; and C1 reached the highest segregation ratio of 13.0%.

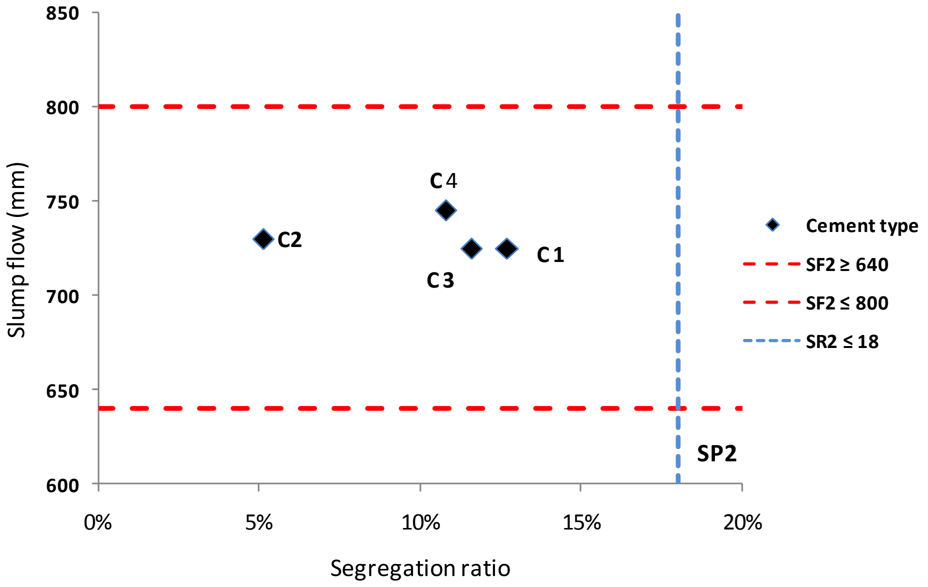


Figure 4.8: Slump flow results relative to segregation ratio results, using SP2

4.9 Effect of extender types on slump flow test – filling ability

This section presents the results obtained from the experiments pertaining to filling ability of SCC as designed according to the European guidelines. Figure 4.9 gives the effect of extenders on the filling ability of SCC for different cements when using SP1 and SP2 respectively, at their optimum concentration.

4.9.1 Fly ash 1 (FA1)

Figure 4.9 (a) shows the effect of the replacement of FA1 at different proportions, from 10% to 40%, when using each type of cement with SP1. It can be seen that the slump flow varied from 517mm to 840mm. For 10% replacement, FA1 increased the flowability of C1 significantly and fell outside the SF2 requirement limits. The opposite effect was observed for C2 and C3: the same replacement of FA1 decreased considerably; and was not within the limitation for SP2 as can be seen in Figure 4.9(b). For FA1 and SP1, C1 and C4 showed an increase in flow with concentration, and C2 and C3 a decrease – except C3 at 40%. For FA1 and SP2 the data was grouped much tighter; and up to 30% replacement, the data was still within the limits. With SP2, the acceptable flow for all the cements was in the range of 10% to 30% replacement, where their slump flow was within the limits.

4.9.2 Fly ash 2 (FA2)

In the presence of SP1, the slump values varied from 625mm to 900mm as shown in Figure 4.9 (c). An increase in FA2 concentration generally increased the slump flow. For C1 and C4 from about 20% the flow rates were outside the limits whereas for C2 and C3 most of the results were within the limits. All the cements behaved in much the same way in the presence of SP2 where the increase in FA2 caused a similar increase in their slump flow, as shown in Figure 4.9 (d). No cement showed acceptable flowability because most of the slump flow values were outside the limits.

4.9.3 Slag

The variation of slump flow values caused by slag replacement for all the cements when using SP1, were between 640 mm and 900 mm as shown in Figure 4.9 (e). It can be seen that for C1 and C4 the slump values fell outside the specifications for all the slag replacement while for C3 and C2 the slump flow were within limits up to 60% replacement. The effect of slag on cements in the presence of SP2 is presented in Figure 4.9 (f). The replacement of slag at different proportions seemed to have the same effect on all the cements; the increase in concentration of slag caused an increase in slump flow for all cements and the slump flow values were over the limit.

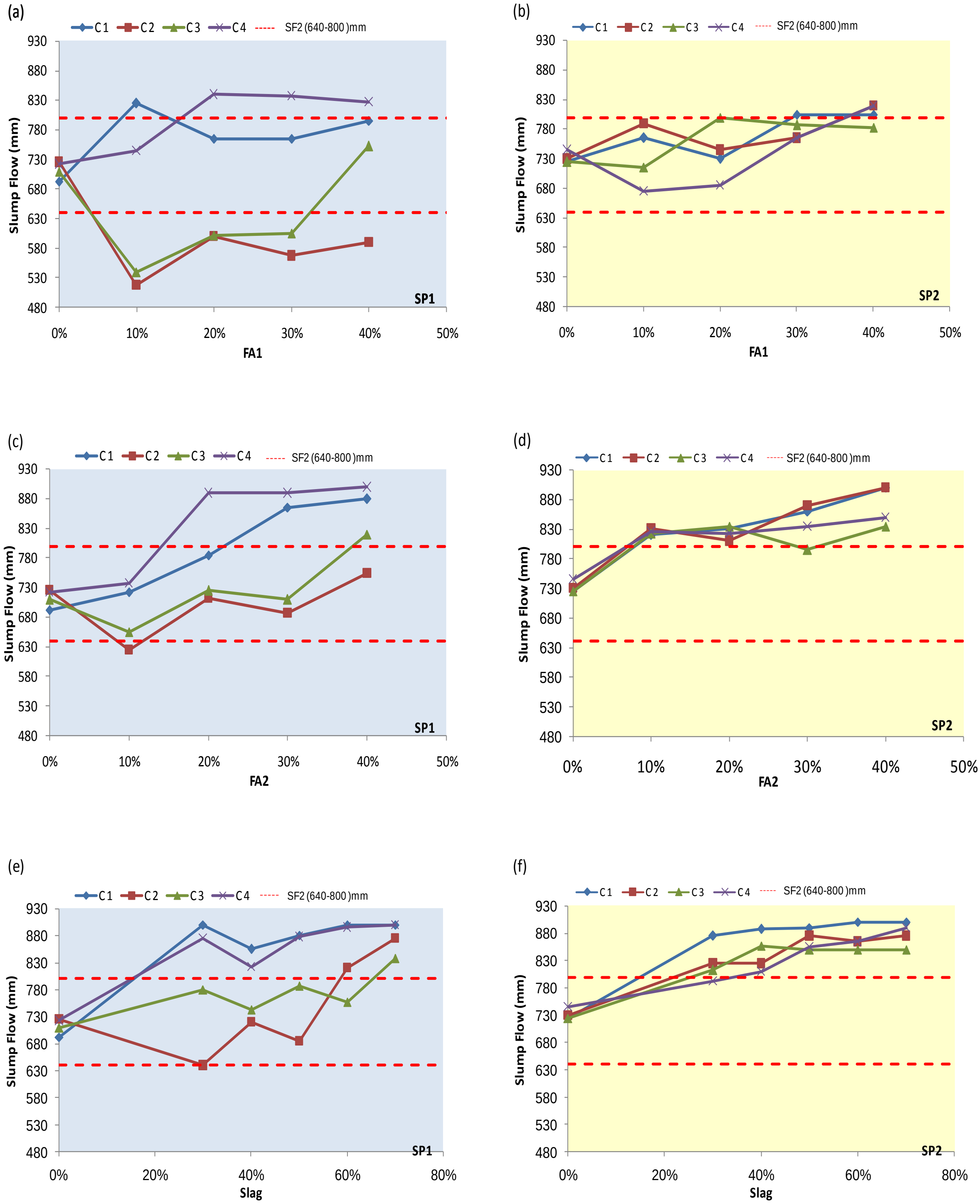


Figure 4.9: The effect of extender types on the slump flow test

4.10 Effect of extender types on segregation ratio – segregation resistance

In this section the segregation ratio results are presented. The effect of FAs and slag replacement on cements in the presence of both SP1 and SP2 are as presented in Figure 4.10 (a–f).

4.10.1 Fly ash 1 (FA1)

The replacement of FA1 when using SP1 as for Figure 4.10 (a) had the same effect on C2 and C3 which showed a resistance to segregation ability within the limits required at any replacement values. C1 and C4 exhibited segregation ratios outside the required limits at any FA1 replacement – except for C4 at 10%. In the presence of SP2, the increase in FA1 caused C1, C2, and C3 segregation ratio values to increase, following a similar trend. However, these values were above the allowable value as shown in Figure 4.10 (b). C4 behaved similarly, except at 10% replacement which was within limits.

4.10.2 Fly ash 2 (FA2)

The effect of FA2 on cements when using SP1 is as shown in Figure 4.10 (c). C1 and C4, as well as C2 and C3 are grouped together. C2 shows resistance to segregation over the whole range of FA2 replacements, whereas C3 shows resistance only up to 20%. For C1 and C4, no replacement is possible with FA2. The results are worse for SP2 than for SP1, as only C4 can be replaced up to 20% with FA2. Figure 4.10 (d) shows the influence of FA2 on the segregation resistance property of all cements with SP2. Besides C4 at 10% and 20% replacement, all cements gave values that were above the limits at any FA2 replacement.

4.10.3 Slag

Figure 4.10 (e) and (f) demonstrate the effect of slag replacement on segregation property of all cements in the presence of SP1 and SP2 respectively. Figure 4.10 (e) shows that only C2 is within the segregation ratio limits–up to 60% replacement. Figure 4.10 (f) shows that with SP2 all cements experienced unacceptable segregation ratio values varying from 21% to 83%, when replaced with slag.

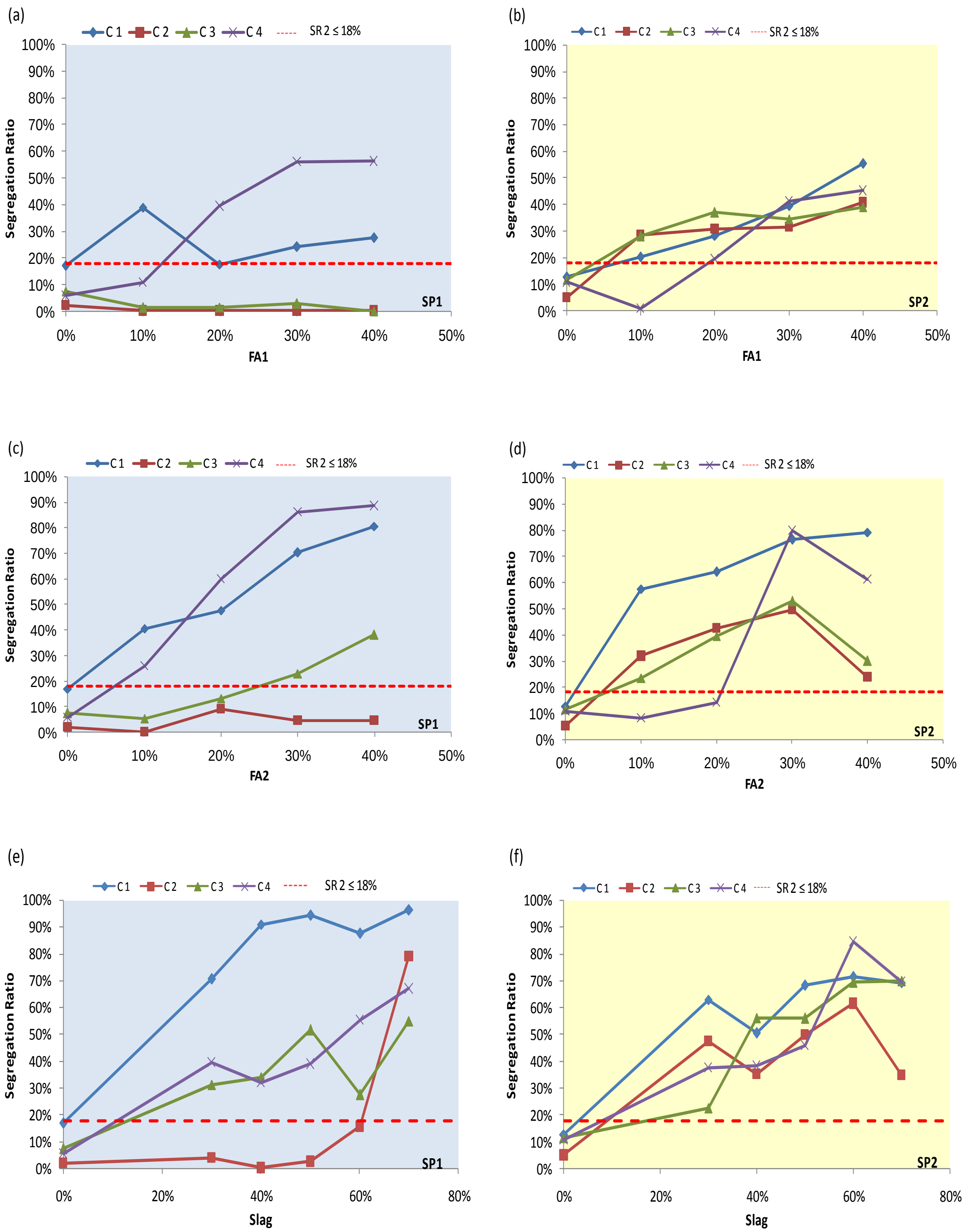


Figure 4.10: The effect of extender types on the segregation ratio

4.11 Effect of extender types on passing ratio – passing/filling ability

All the L-box results were very similar and achieved passing ratios between 0.7 and 1.1 as illustrated in Figure 4.11 (a–f). This is within the specified limit of ≥ 0.75 as required for PA1 and PA2 as set out in the European specification (2005).

4.11.1 Fly ash 1 (FA1)

The passing ability for cements in the presence of SP1 is depicted in Figure 4.11 (a) and (b). Superplasticiser SP2 performed better overall than SP1 for all replacement concentrations of FA1, FA2 and slag. Using SP1, many of the results were within limits. The exceptions were when FA1 was used as a replacement for C2 and C3.

4.11.2 Fly ash 2 (FA2)

The effect of FA2 on cements with SP1 is shown in Figure 4.11 (c). Compared to their base mix, there was minor effect noticed for C1, C3 and C4 when FA2 was partially replaced. C2 behaved differently and was mostly out of the specification. Figure 4.11 (d) shows the effect of FA2 on cements with SP2. FA2 replacement did not affect the passing ratio of cements C1, C2, C3 and C4 compared to their base mixes. With SP2, all cements were within the limits when FA2 was partially replaced.

4.11.3 Slag

The effect of slag replacement on cements with SP1 and SP2 is shown in Figure 4.11 (e) and (f) respectively. For cements with SP1, it can be seen that C1, C3 and C4 did not show any change at all with the amount of slag replacement. Slag in cements with SP2 did not show a change in the passing ratio value. That is, all the cements had almost the same passing ratio values at all the amounts of slag replacement. All cements experienced passing ratio values that were within the limits required.

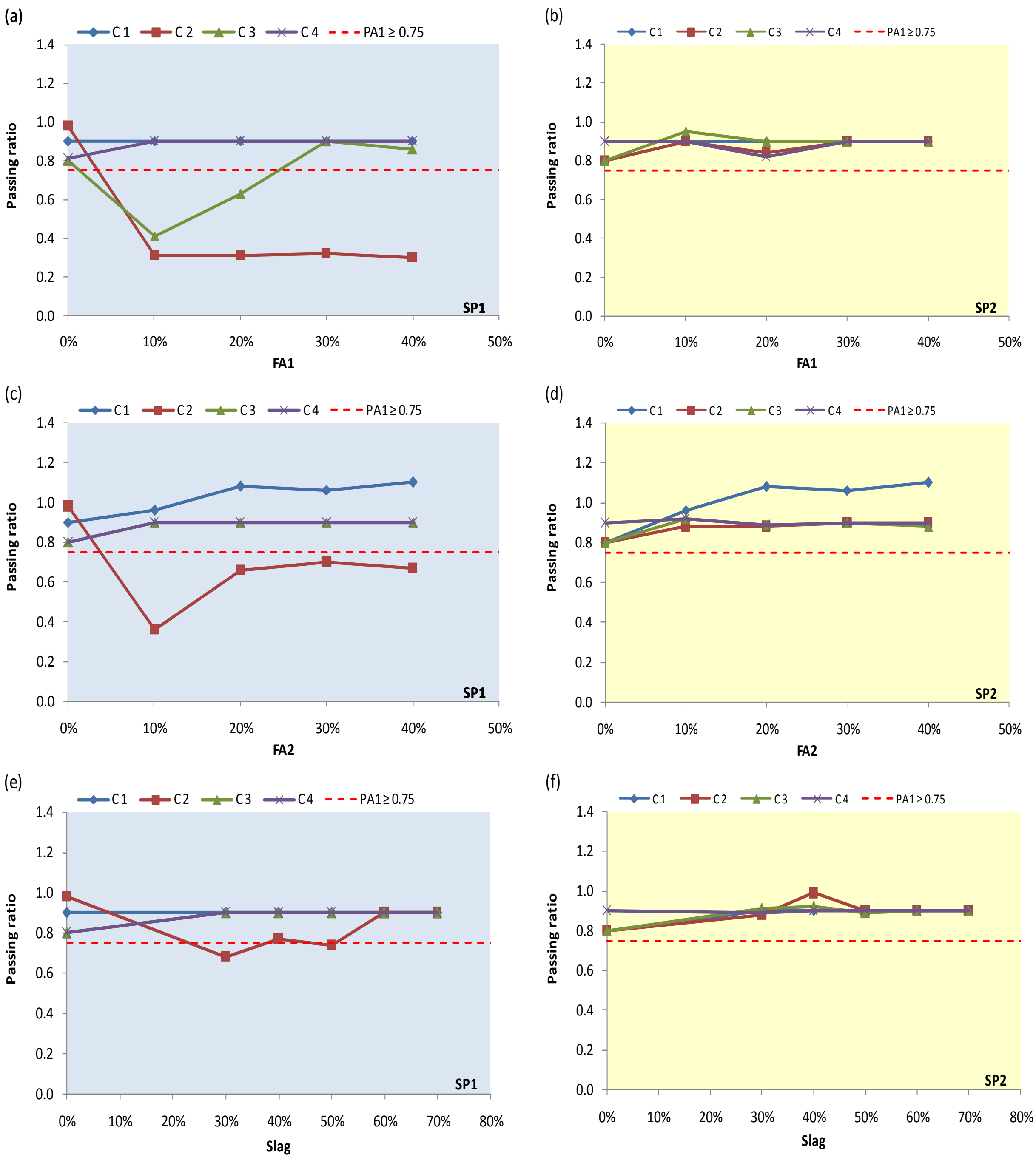


Figure 4.11: The effect of extender types on passing ability

4.12 Effect of extender types on compressive strength

The effect of the FA1, FA2 and slag with SP1 and SP2 can be seen in Figure 4.12 (a–f). Individual compressive strength was compared to the target compressive strength which was 50MPa at twenty-eight days.

4.12.1 Fly ash 1 (FA1)

Cements with SP1 as illustrated in Figure 4.12 (a), experienced a decrease in compressive strength when replacing the cement with FA1. It can be observed that all cements reached the target strength at all amounts of FA1 replacement – up to 30%, but the increase in FA1 concentrations caused a decrease in compressive strength at twenty-eight days. From Figure 4.12 (b), it can be seen that SP2 has increased the compressive strength over the target strength, for all cements at all concentrations of FA1. There is little fluctuation in strength, with increase of FA1 concentration of up to 30% cement replacement.

4.12.2 Fly ash 2 (FA2)

Figure 4.12 (c) presented the effect of FA2 on all the cements with SP1. Compared to the control mix, C1, C2, and C3 show a decrease in compressive strength with an increase in FA2 concentrations, while C4 behaved in the same way, except at 40% replacement where the strength brutally increased and over-passed the target value. Cements with SP2, as seen in Figure 4.12 (d), show the change in compressive strength due to the introduction of FA2 in the mix. It is remarkable that C1, C3 and C4 compressive strengths are inversely proportional to FA2 concentration; there was not much difference. The FA2 in C2 causes the strength to increase incredibly – up to more than 85 MPa; but it shows certain insensitivity to the increase in FA2 concentration as the compressive strength seems to be the same for all the amount of FA2 replacement. When the concentration of FA2 increased, the compressive strengths decreased. However, all the cements experienced strength above the target strength in all cases of FA2 replacement.

4.12.3 Slag

The effect of slag in cements when combined with SP1 and SP2 is demonstrated in Figure 4.12 (e) and (f) respectively. In presence of SP1, slag in C1, C2 and C3 increased the compressive strength and remained at the same range values between 50 MPa and 70 MPa. Slag in C4: increasing the concentration of about 40% to 70%, the strength increased and surpassed the target strength. In the presence of SP2 the compressive strength was very high above the target strength in all cases.

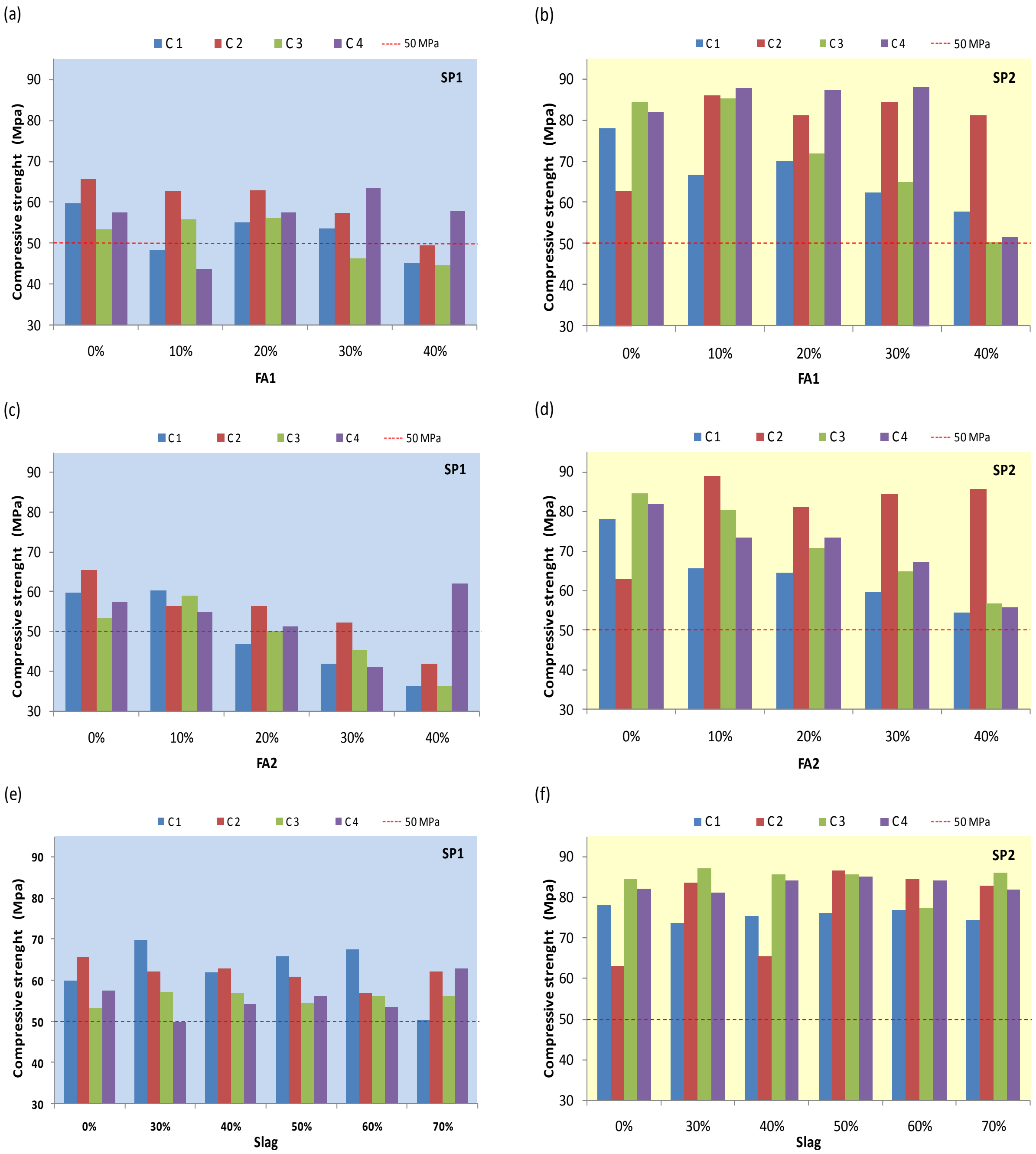


Figure 4.12: The effect of extender types on compressive strength

4.13 Conclusion

The results gathered for the project was done in accordance with the European guidelines for self-compacting concrete. Only the relevant data is presented in this chapter. The remainder of the results are presented in the Appendices (A, B, C, D, E, F, G and H).

CHAPTER 5

Chapter 5 Discussion

In this chapter the results presented in Chapter 4 are discussed and interpreted to determine the effect of the extender types on different cements. The optimisation of superplasticisers and limestone is also discussed. Each extender type is examined individually and compared to the test results obtained in the original sufficient base mix. The correlation between the observed SCC properties and cement characteristics is attempted.

5.1 Sieve Analysis of fine material

It is crucial to ensure that the fines in the sand are monitored at a regular basis and that correction be made if necessary. Such corrections will include sieving the sand through different size sieves and adding different portions to get the required grading. Another grading analysis should be done after combining all the different proportions to ensure that the correct grading is achieved. Organic material and clay content can complicate such a process and therefore it is crucial to have quality control. Clay particles can stick to the sand grains even during sieving and it might be required to wash the sand before achieving the required results. A grading of sand was done and compared to literature examples, when compared to Dune sand it was clear that the Dune sand had a shortcoming of larger particles and can be classified as a Gap-graded sand which could cause problems in SCC mainly on strength properties and most definitely flow behaviour and workability. The Malmesbury sand provided a smooth curve covering all of the particle sizes and could be classified as a Well-graded, round particle sand. The Malmesbury aggregate conformed to most the criteria of good concrete sand and the rounded particles will most definitely decrease surface friction when particles move and thus increase flow ability.

The Malmesbury sand conformed most of all the criteria of good concrete sand and the rounded particles will most definitely decrease surface friction when particles move and thus increase flow ability.

5.2 Optimisation of base mix

The results obtained during the process of the superplasticiser optimisation are presented in Appendices A, B, C, D, E, F, J and K. The optimisation was based on the test methods as set out in Chapter 3, in accordance with the European standards. From Figure 4.1 and Table 5.1, it is evident that the flowability/filling ability increased as the amount of superplasticiser was increased. Mix number C1.3, with a superplasticiser dosage of 1.05% was the closest to the centre of the SF2 specified limits. Nine mixes with different superplasticiser dosages were made, starting with the lowest end of the recommended range of the superplasticiser manufacturer. Figure 4.1 shows the results for these nine mixes and their slump flow spreads. The first batch with 0.85% superplasticiser content proved to be very stiff, and superplasticiser dosages were increased to 1.2% (mix No. C1.8); this proved to be very fluid, with segregation and some bleeding evident.

The resulting segregation and SF2 spread showed that the superplasticiser content was too high; the content was then reduced to 1.15%. This mix showed more promise as the slight reduction of 0.05% in dosage delivered a more coherent SCC mix with no bleeding visible but segregation still evident. The mean spread was 715 mm with a T_{500} time of 1.5 seconds, classifying it as SF2 SCC mix. These results were still deemed unsatisfactory and the superplasticiser dosage was reduced by 0.1% to 1.05%.The 1.05% dosage delivered a very homogeneous and coherent mix No. C1.3. Once the flow stopped, there were no signs of segregation: an even layer of stone and paste distribution was visible with no bleeding around the edges of the SCC slump. The slump spread also was within the SF2 category at 640mm to 800 mm and the T_{500} time was classified as VS2 at 1,23 seconds.

The V-funnel results are an indication of the viscosity/flowability of the mixture. The V-funnel results are depicted in Figure 4.1 (c) and indicate that all the mixtures were within the VF1 limit, below ten seconds. Additional testing was done, and it was confirmed that the mix achieved the required segregation resistance to be within the SR2 limits. As seen in Figure 4.1 (e) the segregation percentage increased as the amount of superplasticiser was increased.

For optimisation of the limestone, the same testing procedures used in the optimisation of the superplasticiser were followed. The results for the optimisation of limestone are displayed in Figure 4.1. From Figure 4.1 (b) it is evident that the adding of limestone had a stiffening effect, reducing the flowability of the mixes. Only mix C1.12 with a limestone volume of 35% was within the SF2 slump flow specified limits. Referring to Figure 4.1 (d), all the V-funnel test results were within the specified VF1 limit – below ten seconds. Test C1.13 with 35% limestone as seen in Figure 4.1 (f) was within the SR2 segregation resistance specified limits. With all the results considered, it was evident that the 35% limestone volume was the most suitable amount to use in the sufficient base mix.

A superplasticiser dosage of 1.05% and 35% limestone volume proved to be the optimum content for the SCC mix design based for C1 on the slump flow, T_{500} and segregation ratio tests. Mix C1.13 was then made using this sufficient mix design, and all tests fell within the prescribed boundaries for SCC as set out in the European guidelines for SCC (2005).

The above optimisation procedure was also conducted for the other three cements used in this study, including the two different types of superplasticiser. The resulting data is illustrated in the Appendices (B, C, D, E, F, J, and K). In Table 5.1 the results of the slump flow, time flow and segregation ratio for C1 – using SP1 and limestone concentration – are presented.

Table 5.1: The effect of SP1 dosage and limestone concentration on C1

Mix Number	% SP dosage	% Limestone concentration	Slump flow (mm)	V-funnel time (sec)	Segregation Ratio
C1.1	0.85	35	585	8.3	10.3%
C1.2	0.95	35	685	4.7	28.0%
C1.3	1.05	35	715	5.2	28.6%
C1.4	1.10	35	670	5.9	28.0%
C1.5	1.10	35	650	6.1	27.0%
C1.6	1.15	35	735	4.8	27.6%
C1.7	1.20	35	735	5.1	44.4%
C1.8	1.25	35	755	5.9	59.1%
C1.9	1.35	35	800	6.9	80.0%
C1.10	1.05	25	635	4.5	56%
C1.11	1.05	30	590	5.7	48%
C1.12	1.05	35	692.5	5.2	15%
C1.13	1.05	40	577.5	5.9	53%

5.3 Mix optimisation with different superplasticisers

The results of fresh properties of all SCC-sufficient mixes for different superplasticisers are included in Figure 5.1. The final slump flow diameter is commonly used to give an indication of the yield stress, and the T_{500} is measured in the field to give an indication of the viscosity of the concrete. Figures 5.1 and 5.2 show the properties such as slump flow and T_{500} time of SCC mixes.

In terms of slump flow, all sufficient SCC mixes had satisfactory slump flows in the range of 640–800mm, which is an indication of a good flowability. With SP1 and SP2, C2 and C4 produced higher slump flow values than C1 and C3. In addition to the slump flow and T_{500} time tests, V-funnel tests were also performed to assess the flowability and stability of the SCC.

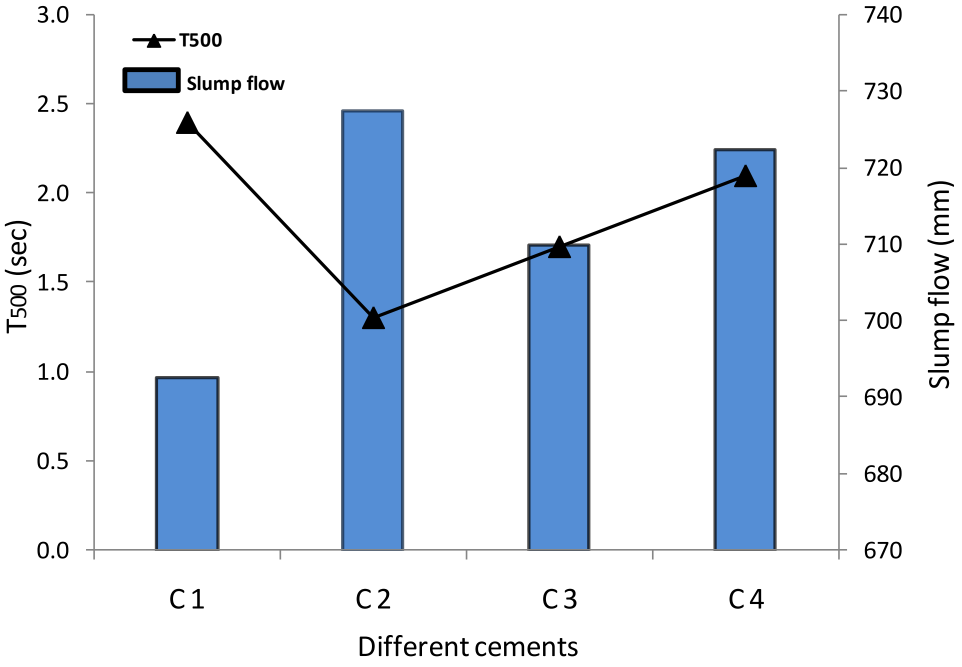


Figure 5.1: Slump flow and T_{500} time of SCC mixes using SP1

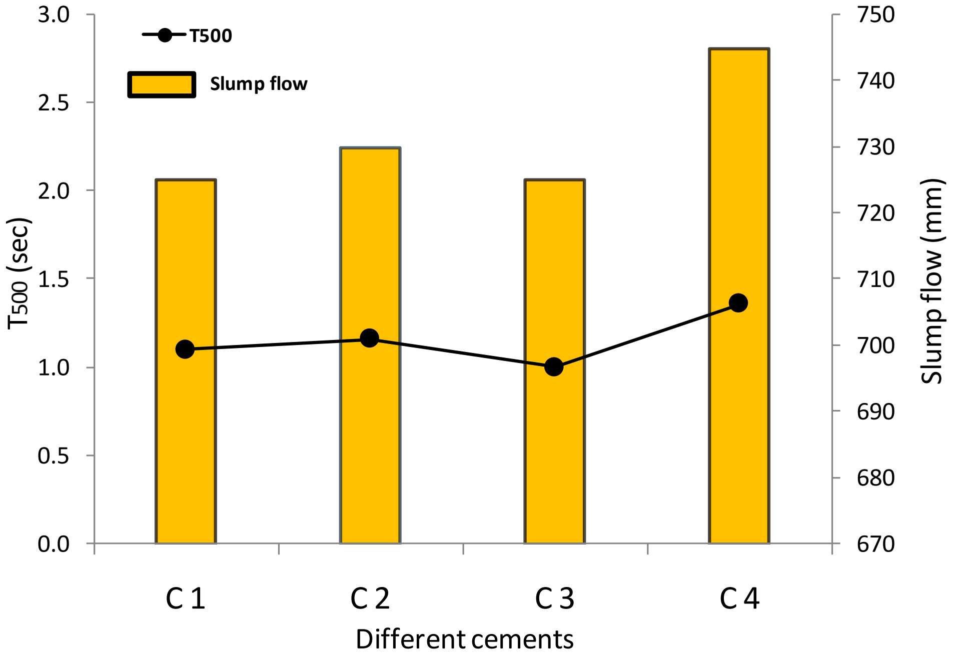


Figure 5.2: Slump flow and T_{500} time of SCC mixes using SP2

5.4 Effect of limestone addition on compressive strength, using different SPs

The effect of limestone filler on SCC in terms of compressive strength at twenty eight days are plotted in Figure 4.4 (a) and (b). Each cube strength result presented is the average of the three cubes tested at the same time; the use of SPs generally increased the strength. Such an increase was not expected as the W/C ratio was kept constant. The limestone addition significantly increases the strength when using SP2 after 28 days compared to SP1. However, $CaCO_3$, which is the major compound of limestone powder, is reported to accelerate the C_3S hydration causing an increase in the compressive strength at early ages. In fact, this is due to the chemical contribution of the calcite to the hydration reactions for each cement leads to the formation of hemicarbonate (Chaignat et al. (2011).

5.5 The effect of extender types on slump flow – filling ability

The effect of fly ash and slag on cement in terms of slump flow differs from when cements are used with SP1 and SP2. It is clear from Figure 4.9 (a) and (b) that FA1 was more compatible with SP2 than SP1. In fact, in the presence of SP2 great SCC mixes were obtained with FA1 compared to SCC with FA1 in the presence of SP1 where only few SCC mixes were obtained at same FA1 concentrations. FA2 in the presence of SP1 provided good flowable SCC mixes as shown in Figure 4.9 (c) compared to FA2 with SP2 addition according to Figure 4.9 (d).

Concerning slag replacement, it was observed that in the presence of SP1 great SCC mixes were obtained for all cements at different concentrations – except cements C1 and C4, whereas with the addition of SP2, there was no possibility to obtain good flowable SCC at any concentration.

All these changes occurred because of the difference in chemical compound concentration; physical characteristics of each type of cement; as well as the chemical structure of the superplasticiser used. For instance when using SP1, the slump flow of the mixes increased as the fineness of the cement decreased: C2 –the coarsest cement – had the lowest slump flow; whereas C3 – the finest cement with 3 850 cm^2/gr–had the highest slump flow, as can be seen in Figure 4.9. However, the interaction of cements with SP1 seemed to depend strongly on alkali content. Cements with high alkali content exhibited a high slump flow as for C1 with 0.74% and C4 with 0.33%, while the ones with low alkali content exhibited the lowest slump flow. The same behaviour was observed by Flatt and Houst

(2001), who found that the workability (slump flow) of mixes prepared with the low alkali cements was reduced, compared to that of the mixes with higher alkali cements.

When using SP2, the flow behaviour of SCC seemed to be influenced by the concentration of C_3A in each cement-type in most of the mixes. For instance, C1 with the highest concentration of 3.92% resulted in the lowest slump flow; while C4 with the lowest C_3A content resulted in the highest slump flow. Thus, the workability of SCC in the presence of SP2 was found to be inversely proportional to the content of C_3A content in such a way that cement with high C_3A exhibited the lowest slump flow when using SP2 (Vikan, 2007).

However, C3 was supposed to have the highest slump flow because of its low C_3A contents. The findings of Golaszewski (2008) helped to explain this observed behaviour: there is a strong correlation between the C_3A content in cement and its corresponding surface area. C3 has the highest surface area and lowest content of C_3A. This leads to an increase in yield stress, causing the slump flow value to decrease. In addition, Vikan (2007) affirmed that the molecules of polycarboxylates are more absorbed by C_3A in the early hydration phase leaving small amounts of SP in the solution that reduce the steric effect of SP and cement interaction.

5.6 The effect of extender type on segregation ratio – segregation resistance

The performance of SCC in terms of segregation resistance, when using fly ash and slag differs from one cement-type to another depending on SP used. From Figure 4.10 (b), it is seen that FA1 was not compatible with SP2 as only one SCC mix was obtained from all the mixes attempted. While there was great segregation resistance, SCC obtained for all cements except C1 and C4 at different replacements. The same behaviour was observed for FA2 in the presence of SP1 and SP2. With the use of slag, the incompatibility of SPs were observed with both SP1 and SP2 due to the fact that there was no SCC with good segregation resistance obtained with the addition of these SPs for all cements – except C2 in the presence of SP1.

The most significant parameters affecting the fluidity of mixes are the alkali content and superplasticiser-type and concentration. However, the interaction of cements with SPs seemed to depend strongly on alkali content. As we can see from Table 3.2, cement with high alkali content exhibited a high segregation ratio as for C1 with 0.74% and C4 with 0.33%, while the ones with low alkali content, C2 and C3 with 0.41 and 0.29% respectively, exhibited the lowest segregation ratio. The use of limestone and extenders improved fluidity to some extent. The utilisation of a VMA can decrease fluidity. From the segregation results, it is evident that the addition of fly ash had a positive effect on C2 and C3, reducing the segregation resistance over the range that the cements were replaced by fly ash. C1 and C4 were negatively affected by the addition of fly ash.

5.7 The effect of extender type on passing ratio – passing ability

From Figure 4.11 (a–d), FA replacement in all cements with SP2 resulted in SCC mixes with a great passing ability. However, FA replacement in C4 had a limited passing ability in the presence of both SPs. FA1 replacements in C1 with SP1 produced the same behaviour when using SP2. FA2 replacement in C1 behaved the same in the presence of both SPs. At 10% FA replacement in C2 with SP1, the cement had the same passing ratio; and at other concentrations it was affected more by FA2 than FA1. At the same concentration of FAs, C3 seemed to be more affected when using FA1 and SP1. However, SP2 affected the cements at any concentration of FA in the same way with almost similar passing ratio values. Cements were very insensitive when using slag replacement with SP2: there was no change in the passing ratio when compared to the base mixes. For SP1 the same behaviour was noticed for all cements, except C2 which showed changes and became insensitive between 60% and 70% slag replacement. Nevertheless, SP1 and SP2 for all the cements – except C2 – when using slag as an extender, gave almost the same passing ratio values above the limitation required.

5.8 The effect of extender type on compressive strength

Comparing graphs in Figure 4.12, it can be seen that SP2 provided SCC mixes with higher compressive strengths than SP1, regardless of the extender used. The compressive strength of cements was not affected by the type of extender used as observed in Figure 4.13 (a) and (c) where FA1 performed in the same manner as FA2 in the presence of SP1. The strength of cements at each concentration of these extenders does not vary at all. The same effect when using SP2 is observed for FA1 and FA2. However, for SP2 the compressive strength is above the target strength independently of the extender used. Compared to FA, compressive strengths are improved when slag replacement is used in the presence of cements with both SPs. But compared to the base mixes, slag doesn't show any effect on any of the cements in the presence of both SPs.

Generally, the compressive strength decreased will increase in the percentage of extenders when using SP1. Replacing OPC with extenders caused a reduction in the compressive strength after twenty-eight days, as would be expected. Compressive strength increased as the alkali content in the cements increased. This was observed in equivalent sodium sulphate Na_2O solution: the test results showed that the strength in sodium sulphate solution was much less pronounced than that in magnesium sulphate solution.

5.9 Summary of effects of extender types on properties of SCC

As discussed in sections 5.4-5.8, the four different properties which were used to determine whether the SCC was good enough after extender replacement were flowability, filling ability, passing ability and compressive strength. The ideal mix for each extender replacement should meet the requirements for each of these properties. Table 5.2 gives a summary of numerous cements when replaced with different compositions of various extenders using two different superplasticisers. In Table 5.2, the ticks (√) represent a mix which passes a property test; and a negative result is represented by the symbol x.

In summary, the result matrix shows that only five mixes passed all the property tests. (These mixes are highlighted in red shadings). Of the 416 tests conducted with the different mixes, only five mixes tested could be classified as an SCC. The mix design was not changed and the superplasticiser was not optimised when replacing the cement with extenders as this would have added more variables. This however influenced the results negatively. The objective was to see how sensitive the SCC properties were when replacing the different cements with fly ash and slag at different percentages. Only five were able to meet the requirements due to a number of reasons which are discussed in depth.

Some important properties such as specific surface area; particle-size distribution; sulphate type and content; C_3A; and alkali content can all affect different cements (Aiad, 2003) which in turn have an effect on the flowability and segregation of SCC. In the next section, an attempt is made to determine the nexus between the chemical and physical properties of the different cements on the properties of SCC (flow, segregation resistance and compressive strength) when extended with fly ash and slag. These relationships are very complex.

Table 5.2: Effect of various cements on SCC when replaced with different compositions of various extenders using two different superplasticisers

SPs	Extenders replacement		Slump flow/Filling ability				Segregation ratio/Segregation resistance				Passing ratio/Passing ability				Compressive strength at 28 days			
			C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
SP1	OPM	0%	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	FA1	10%	X	X	X	√	X	√	√	√	√	X	X	√	X	√	√	X
		20%	√	X	X	X	X	√	√	X	√	X	X	√	√	√	√	√
		30%	√	X	X	X	X	√	√	X	√	X	√	√	√	X	X	√
		40%	√	X	√	X	X	√	√	X	√	X	√	√	√	X	√	√
	FA2	10%	√	X	√	√	X	√	√	X	√	X	√	√	√	√	√	√
		20%	√	√	√	X	X	√	√	X	√	X	√	√	X	√	√	√
		30%	X	√	√	X	X	√	X	X	√	X	√	√	X	√	X	X
		40%	X	√	X	X	X	√	X	X	√	X	√	√	X	X	X	√
	Slag	30%	X	√	√	X	X	√	X	X	√	X	√	√	√	√	√	X
		40%	X	√	√	X	X	√	X	X	√	√	√	√	√	√	√	√
		50%	X	√	√	X	X	√	X	X	√	√	√	√	√	√	√	√
		60%	X	X	√	X	X	√	X	X	√	√	√	√	√	√	√	√
		70%	X	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√
SP2	OPM	0%	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	FA1	10%	√	√	√	√	X	X	X	√	√	√	√	√	√	√	√	√
		20%	√	√	√	√	X	X	X	X	√	√	√	√	√	√	√	√
		30%	X	√	√	√	X	X	X	X	√	√	√	√	√	√	√	√
		40%	X	X	√	X	X	X	X	X	√	√	√	√	√	√	√	√
	FA2	10%	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√	√
		20%	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√	√
		30%	X	X	√	X	X	X	X	X	√	√	√	√	√	√	√	√
		40%	X	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√
	Slag	30%	X	X	X	√	X	X	X	X	√	√	√	√	√	√	√	√
		40%	X	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√
		50%	X	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√
		60%	X	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√
		70%	X	X	X	X	X	X	X	X	√	√	√	√	√	√	√	√

5.9.1 Interaction of extenders with cement compounds in SCC using SP1

The effect of extenders such as FA1, FA2 and slag on workability of SCC considering the cement compound content in the cement are discussed according to the graphs below. It was of great importance to see how the physical and chemical properties of these cements interacted with the extenders at different replacements in the presence and absence of SPs. The effectiveness of SCC depends on some requirement or limitations as discussed previously – regarding the slump flow, segregation resistance and compressive strength properties. The regulating of the optimum content of cement compound and physical properties that the cement-type should contain was conducted, as described in Chapter 4.

5.9.2 FA1 replacement with SP1 and SP2

Figures 5.3 and 5.4 illustrate the effect of FA1 replacement in the presence of SP1 on SCC properties, based on the chemical composition of cements such as C_3A and C_3S. For the workability and hardened concrete, a SCC should meet the limitations of slump flow and segregation, comprised in the interval of 640 mm and 800 mm respectively, and less or equal to 18% (EFNARC, 2005) meeting the target compressive strength (50 MPa). Concerning cement-compound content, focus was only put on the concentration, allowing the cement replacement to fulfil all the SCC properties simultaneously. Thus, the C_3A concentration of interest was in the range of 3.2% to 3.3% as it can be seen on Figure 5.3 (a–c). Within this interval, the cement replacement could be done up to 40% of FA1. Similarly: for C_3S, the optimum interval was found to be in the interval of 53% to 53.8%, allowing a cement replacement up to 40% of FA1. Whilst the equivalent alkali content was found to be in the range of 0.35% to 0.4% as shown in Figure 5.4 (a–c), in this region the cement replacement could be done up to 40% of FA1.

Regarding the physical properties of cement, such as surface area, FA1 replacement in the presence of SP1 seemed to be effective: as seen in Figure 5.4 (d–f) in the range of 3 680 cm^2/gr and 3 720 cm^2/gr, allowing up to 40% replacement. However, when using SP2 as seen in Figures 5.5 and 5.6, the effective ranges of C_3A, C_3S, $Na_2O(eq)$ and surface area were found to be around 2.15% to 2.67%; 53% to 59.1%; 0.36% to 0.68% and 3 770 cm^2/gr to 4 090 cm^2/gr respectively. Contrary to the case of using SP1, FA1 replacement could only be done up to 10% in the presence of SP2. In fact, above this replacement content, segregation resistance seemed to be out of the specifications. For all the cements, only C4 was found to provide a SCC mix within all these ranges when using FA1 in the presence of SP2. The above chemical and physical limitations for each replacement are summarised in Table 5.3.

Table 5.3: Physical and chemical properties of the cements when replaced with FA1, using two different superplasticisers.

The Properties of different compounds of cement	Extender replacement	Different cements			
	FA1 with SP1	C1	C2	C3	C4
C3A content range	3.2–3.3	x	x	x	x
C3S content range	53–53.8	x	x	x	x
Na_2O (eq) content	0.35–0.4	x	√	x	x
Surface area range (cm^2/g)	3 680–3 720	x	x	x	x
	FA1 with SP2	C1	C2	C3	C4
C3A content range	2.15–2.67	x	x	x	√
C3S content range	53–59.1	x	x	x	√
Na_2O (eq) content	0.36–0.68	x	x	x	√
Surface area range (cm^2/g)	3 770–4 090	x	x	x	√

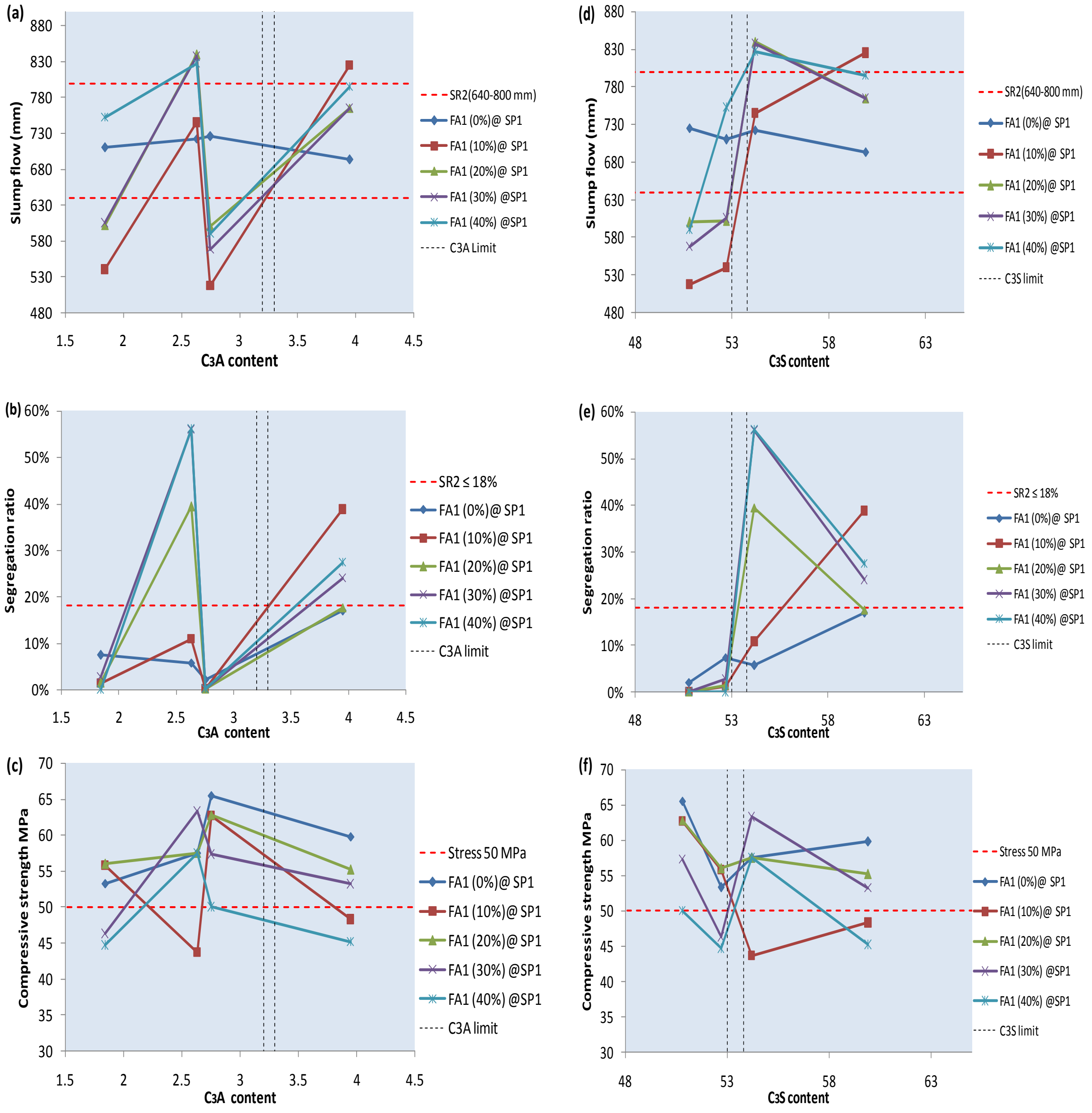


Figure 5.3 : Interaction of FA1 extender with cement compounds C_3A and C_3S on SCC properties, using SP1

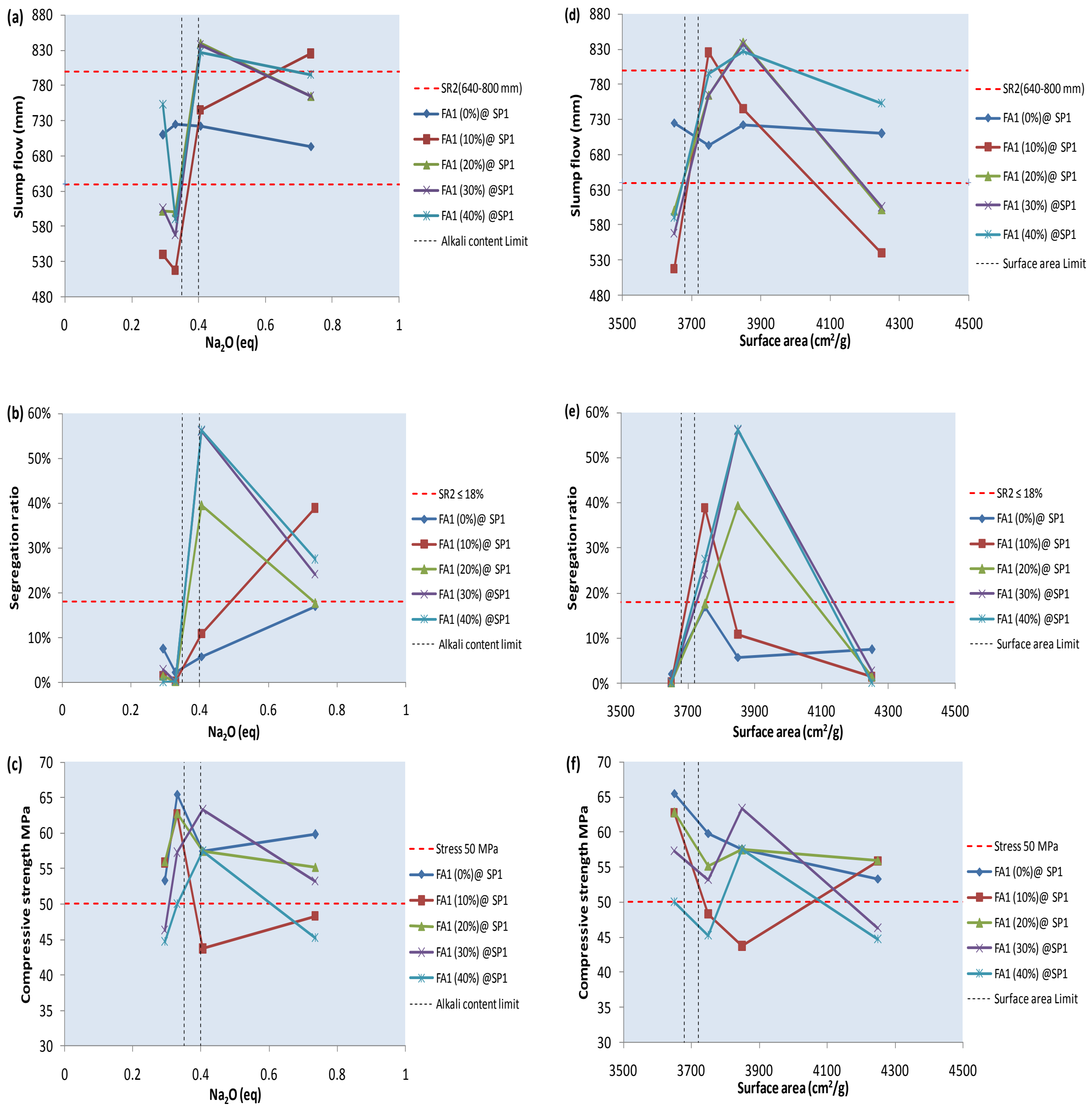


Figure 5.4 : Interaction of FA1 extender with cement compounds, alkali content and surface area on SCC properties, using SP1.

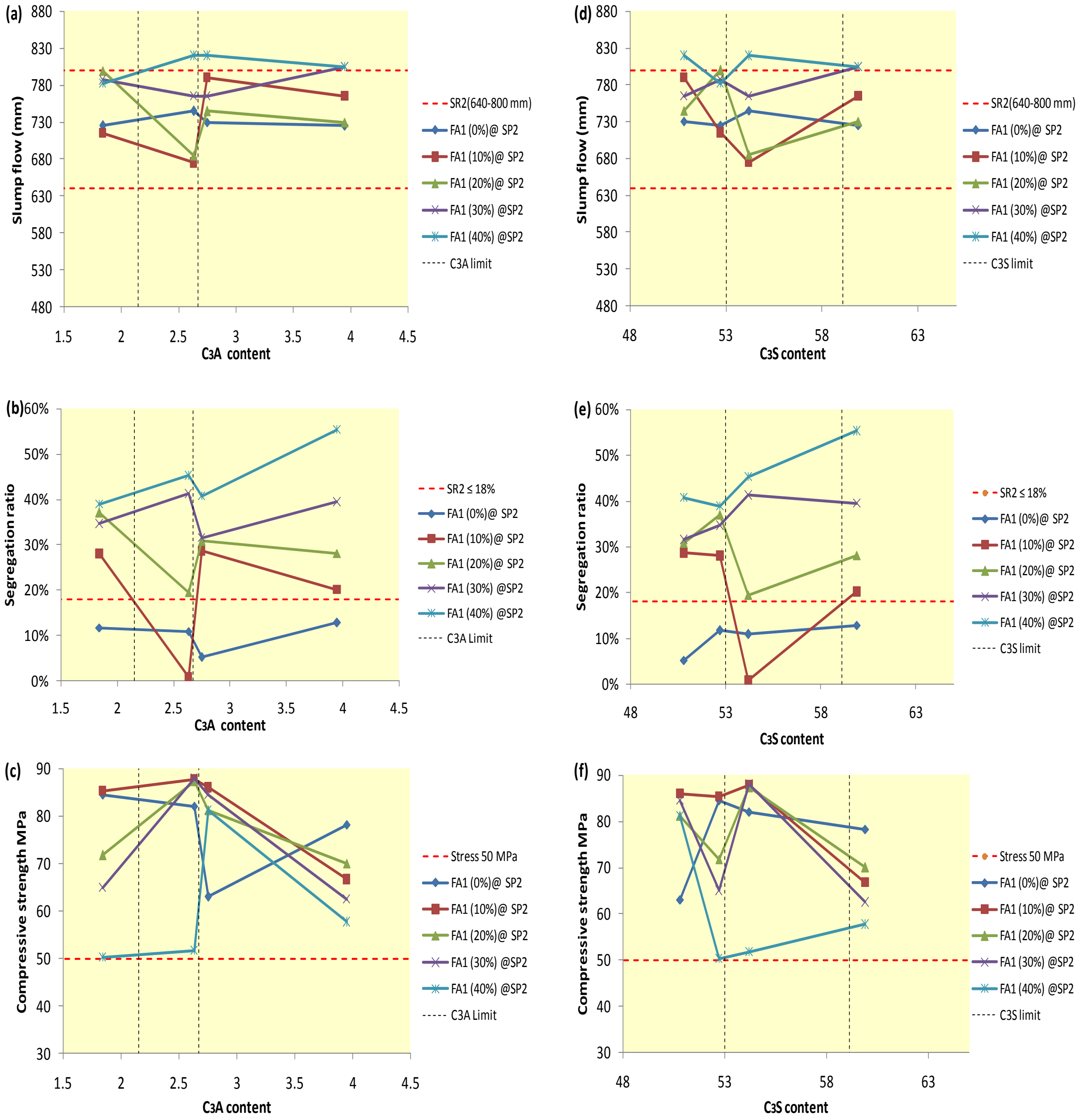


Figure 5.5 : Interaction of FA1 extender with cement compounds C_3A and C_3S on SCC properties, using SP2

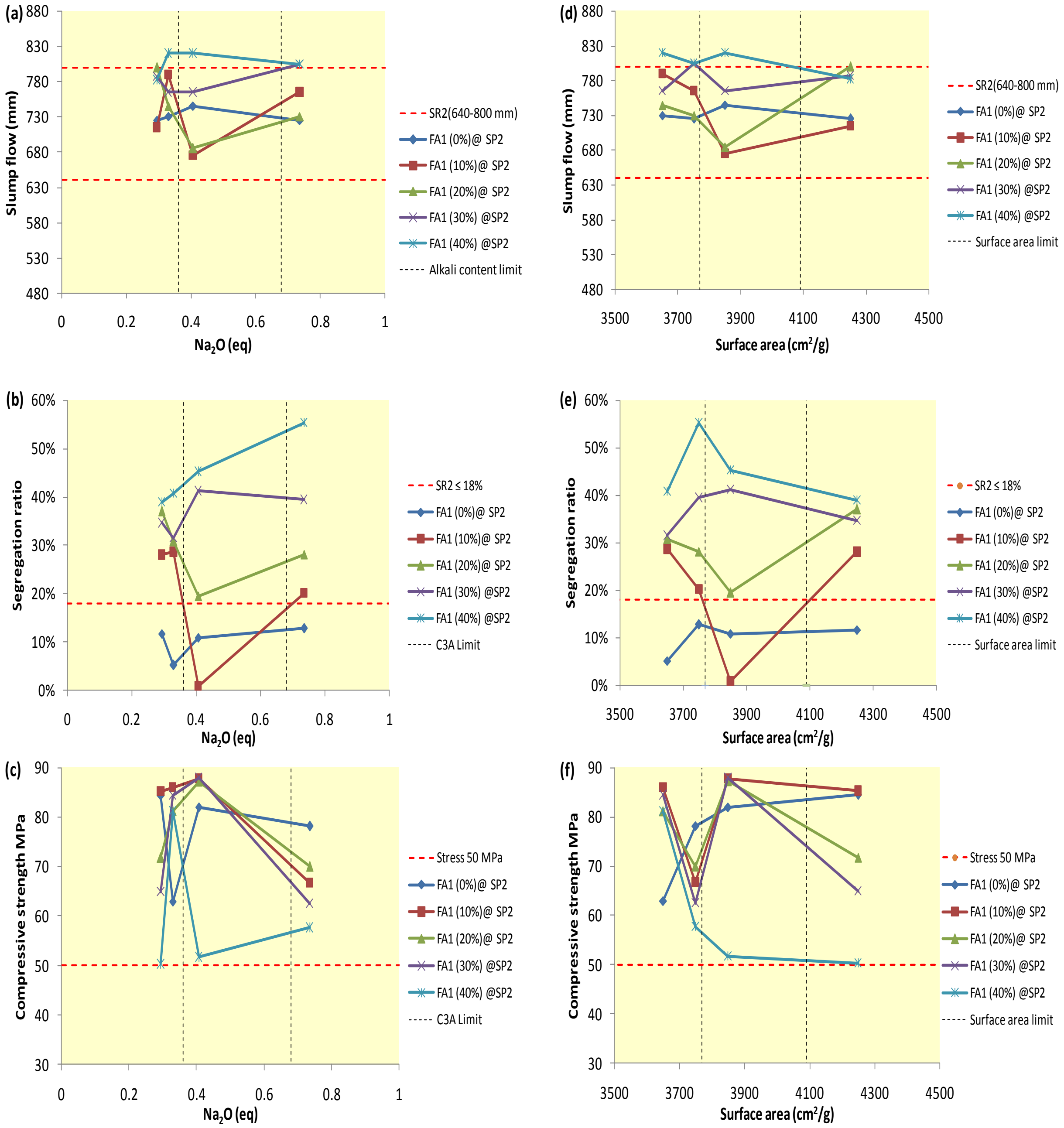


Figure 5.6 : Interaction of FA1 extender with cement compounds, alkali content and surface area on SCC properties, using SP2

5.9.3 FA2 replacement with SP1 and SP2

The cement replacement with FA2 in the presence of SP1 could go up to 40% provided that C_3A ranges from 2.8% to 2.95%; C_3S from 50.8% to 52%: Na_2O(eq) from 0.31% to 0.35%; and the surface area from 3650cm^2/gr to 3 690cm^2/gr. This can be seen in Figures L.1 and L.2 in Appendix L; when these chemical compounds and surface area prerequisites were met, it could be seen that up to 40% FA2 could be replaced when using SP1. All mixes produced SCC with good flowability and high resistance to segregation, reaching in all cases the target compressive strength 50MPa. However, when replacing the cement with FA2 using SP2 as shown in Figures L.3 and L.4 in Appendix L, none of the replacement concentrations met the SCC properties simultaneously within a very well-defined interval of C_3A, C_3S, Na_2Oeq or surface area. Consequently, there was no possibility to define in which range the chemical and physical characteristics of cement should fall, in order to have an SCC that exhibited an acceptable flowability at a high segregation resistance and compressive strength – at the same time. For instance, all the replacement of FA2 in the presence of SP2 met the target compressive strength but could not provide the required segregation ratio and slump flow. Thus, in defining the prerequisite range of cement compound and surface area, these replacements were thrown out as presented in Figure 5.6. The above chemical and physical limitations for each replacement are summarised in Table 5.4.

Table 5.4: Physical and chemical properties of the cements when replaced with FA2 using two different superplasticisers.

The Properties of different compounds of cement	Extender replacement	Different cements			
	FA2 with SP1	C1	C2	C3	C4
C3A content range	2.8–2.95	x	x	x	x
C3S content range	50.8–52	x	√	x	x
Na_2O (eq) content range	0.31–0.35	x	x	x	√
Surface area range (cm^2/g)	3650–3690	x	√	x	x
	FA2 with SP2	C1	C2	C3	C4
C3A content range	Out of limits	x	x	x	x
C3S content range	Out of limits	x	x	x	x
Na_2O (eq) content range	Out of limits	x	x	x	x
Surface area range (cm^2/g)	Out of limits	x	x	x	x

5.9.4 Slag replacement with SP1 and SP2

Analysing the interaction of slag with the different cements in the presence of SPs, Figures M.1 and M.2 in Appendix M revealed that the slag replacement could be done up to 50%, provided that C_3A, C_3S, Na_2O(eq) and surface area be defined respectively within the range of 2.68% to 2.91%; 50.8% to

51.3%; 0.31% to 0.37%; and 3650 cm^2/gr to 3670 cm^2/gr when using SP1. For all the cements, only C2 was found to provide a SCC mix within all these ranges – except alkali content Na_2O(eq) which was a bit higher than range when using FA1 in the presence of SP1. When cements were replaced with slag using SP2 this was not possible. The above chemical and physical limitations for each replacement are summarised in Table 5.5.

Table 5.5: Physical and chemical properties of the cements when replaced with slag using two different superplasticisers.

The Properties of different compounds of cement	Extender replacement	Different cements			
	Slag with SP1	C1	C2	C3	C4
C3A content range	2.68–2.91	x	√	x	√
C3S content range	50.8–51.3	x	√	x	x
Na_2O (eq) content range	0.31–0.37	x	x	x	√
Surface area range (cm^2/g)	3650–3670	x	√	x	x
	Slag with SP2	C1	C2	C3	C4
C3A content range	Out of limits	x	x	x	x
C3S content range	Out of limits	x	x	x	x
Na_2O (eq) content range	Out of limits	x	x	x	x
Surface area range (cm^2/g)	Out of limits	x	x	x	x

5.10 Conclusion

It is clear that the performance of SCC depends on its properties: flowability, passing ability and segregation resistance. These characteristics, in turn, are directly related to the interaction of cement features and the incorporated admixtures: fly ashes, slag and SP. According to the tests, replacement of cement with extenders in order to get a SCC, seemed to depend on the chemical and physical properties of each cement – including the soluble alkali in the mixture, C_3A, C_3S and the surface area. The optimum SCC properties can only be obtained within the recommended region.

CHAPTER 6

Chapter 6 Conclusions and recommendations

6.1 Conclusions

The objective of this project was to investigate the effect of four cements produced by PPC at different factories on a required SCC mix, extended with fly ash and slag at various concentrations and with two different SPs. The tests were done according to the European standard. The properties tested were flowability, passing ability, segregation resistance and compressive strength at seven and 28 days. An attempt was made to link the variation in flow segregation and strength difference to physical and chemical properties of the cements.

Slump flow

All cements experienced good slump flow when using SP2 and FA1. With SP2, all cements did not meet the slump flow requirements when using FA2; and only C2 and C3 were within the limitation when using SP1. FA2 with SP2 caused cement to be very sensitive to FA: the slump flow values were very high compared to those experienced by cements in the presence of SP1. All cements were more sensitive to slag replacement when using SP2, as slump flow values obtained were much higher in this condition – more than when SP1 was used. However, all cements were outside the limitation of slump flow requirement in the presence of SP2.

Segregation resistance

Superplasticiser SP2 increased the segregation ratio values of all cements with FA1, compared to FA1 with SP1. FA2 affected cements in terms of their segregation ratio values more than FA1, in the presence of both SPs. Slag replacement of cements with SP2 segregated without fail at any of the replacement concentrations. At maximum slag replacement (70%) the segregation ratio values were smaller compared to those obtained when using cements with SP1. Only slag replacement in C3 with SP1 gave allowable segregation ratios up to 60% replacement.

Passing ability

For all the cements: when replaced with both fly ashes for all concentrations with SP1, the passing ability of the SCC was good. The effect with SP2 was similar. When using slag as an extender, cements were very insensitive with SP2 regardless of the amount of slag replacement used. The same behaviour was observed for cements with SP1 at all concentrations of slag replacement – except for C2 which performed well, only for 60% to 70% replacement. The passing ratio values of cements – except C2 – seemed not to be affected by the interaction of slag and SPs.

Compressive strength

When using SP2 the compressive strengths were higher than for SP1 for all mixes regardless of extenders used. Compared to fly ash, slag improved the compressive strength of cements for both SPs with higher compressive strength values when using SP2 than when using SP1. The effects of the cement mineralogy and physical characteristics were also investigated. Even though the cements were in the same class, only manufactured at different factories, the cement mineralogy and physical properties varied. The effect of C_3A, C_3S,Na_2O(eq) and surface area of the four cements were found to have an influence on the SCC properties, and optimum ranges were established. Therefore, when using SP1 and FA1 (allowing a replacement of up to 40% of cement), C_3A content in cement should be in the range of 3.2% and 3.3%; C_3S within 53% and 53.8%; Na_2O(eq) within 0.35% and 0.4%; and the surface area should be in the interval of 3 680 cm^2/g to 3 720 cm^2/g.

Similarly, when using SP1 and FA2 (up to 40% replacement), C_3A content should be within 2.8% and 2.95%; C_3S within 50.8% and 52%; Na_2O(eq) within 0.31% and 0.35%; and the surface area within 3 650 cm^2/g and 3 690 cm^2/g. With the same type of superplasticiser – SP1 – slag could only be replaced up to 50%, provided that C_3A was within the range of 2.68% and 2.91%; C_3S was within 50.8% and 51.3%; Na_2O(eq) within 0.31% and0.37%; and the surface area within 3 650cm^2/g and 3 670 cm^2/g.

When using SP2 with different extenders, only FA1 provided a better SCC mix. The replacement could only be done up to 10% of cement with C_3A within the range of 2.15% and 2.67%; C_3S within 53% and 59.1%; Na_2O(eq) within 0.36% and 0.68%; and the surface area within 3 770 cm^2/g and 4 090 cm^2/g.

General

The overall assessment is that cements manufactured at different factories vary enough in terms of chemistry and physical properties to have an effect on an SCC mix. Superplasticisers, even though they are chemically similar, can affect the SCC properties in significantly different ways. It is possible to extend an SCC mix with fly ash and slag, but the effect varies from cement to cement. It is therefore necessary to have an understanding of the sensitivity of SCC to all the variables and do sufficient testing before using the product.

6.2 Recommendations for further research

The research in this project focused on specific materials to compile the required base mix. The base mix consisted of SP1 and SP2, 13 mm crushed aggregate, Malmesbury sand, water, limestone and different OPC cement manufactured by PPC. The results achieved are specific, in conjunction with these materials; and the following recommendations are made to extend this research.

Further research can be done with a different superplasticiser and different limestone types to determine the effect on the mixtures. This will require a study and analysis of the chemical composition and the reactions between the cement, superplasticiser and aggregates.

Research indicating the replacements of the fly ashes and slag, what is required in terms of superplasticiser volume to get the other replacement percentages back to within the prescribed limits as set out in the European standard.

This research can be extended by determining the cause of the severe segregation found with the FA1 and the slag, and to determine what is required to get it back within the prescribed limits as set out in the European standards. The sensitivity of SCC in terms of the sand grading and the effect on the compressive strength can be further investigated. This can include developing the procedures required to manipulate sand to the required grading. Viscosity modifying agents (VMAs) should be investigated as they can control segregation. VMAs were not included in this research as it would have added another variable. The effect of the different cement classes in accordance with the extender types and limestone can be determined.

All the experimental testing was done in accordance with the European standard as there is currently no SCC standard in South Africa. South African standards and guidelines need to be developed in accordance with the South African National Standards and the materials found locally.

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APPENDICES

Appendices

Appendix A. (C1 with SP1)

- Table A.1: Mix proportions for C1 using SP1
- Table A.2: Test results for C1 using SP1
- Figure A.1: Effect of replacing C1 with FA1 on SCC properties at sufficient SP1 concentration
- Figure A.2: Effect of replacing C1 with FA2 on SCC properties at sufficient SP1 concentration
- Figure A.3: Effect of replacing C1 with slag on SCC properties at sufficient SP1 concentration

Table A.1: Mix proportions for C1 using SP1

Mix	Litre	Cementations kg	w/c	Stone kg	Sand kg	Fines kg	SP %	SP kg	CD %	CD kg	Water kg	FA / C	%	Fly Ash kg	Cement kg	S / C %		Slag kg	Cement kg	Variables
1	35	14.63		23.80	33.37	19.751	0.850%	0.168	35%	5.12	6.58		100%		14.630					**SP1**
2				23.80	33.33	19.751	0.950%	0.188	35%	5.12	6.58		100%		14.630					**SP1**
3				23.80	33.28	19.751	1.050%	0.207	35%	5.12	6.58		100%		14.630					**SP1**
4				23.80	33.26	19.751	1.100%	0.217	35%	5.12	6.58		100%		14.630					**SP1**
5				23.80	33.26	19.751	1.100%	0.217	35%	5.12	6.58		100%		14.630					**SP1**
6				23.80	33.23	19.751	1.150%	0.227	35%	5.12	6.58		100%		14.630					**SP1**
7				23.80	33.21	19.751	1.200%	0.237	35%	5.12	6.58		100%		14.630					**SP1**
8				23.80	33.19	19.751	1.250%	0.247	35%	5.12	6.58		100%		14.630					**SP1**
9				23.80	33.14	19.751	1.350%	0.267	35%	5.12	6.58		100%		14.630					**SP1**
10	35	14.63		23.80	34.69	18.288	1.050%	0.192	25%	3.66	6.58		100%		14.630					**LM**
11				23.80	33.99	19.019	1.050%	0.200	30%	4.39	6.58		100%		14.630					**LM**
12				23.80	33.28	19.751	1.050%	0.207	35%	5.12	6.58		100%		14.630					**LM**
13				23.80	32.57	20.482	1.050%	0.215	40%	5.85	6.58		100%		14.630					**LM**
14	35	14.63		23.80	33.10	19.751	1.050%	0.207	35%	5.12	6.58	10%	90%	1.463	13.167					**FA1**
15				23.80	32.91	19.751	1.050%	0.207	35%	5.12	6.58	20%	80%	2.926	11.704					**FA1**
16				23.80	32.73	19.751	1.050%	0.207	35%	5.12	6.58	30%	70%	4.389	10.241					**FA1**
17				23.80	32.54	19.751	1.050%	0.207	35%	5.12	6.58	40%	60%	5.852	8.778					**FA1**
18	35	14.63		23.80	33.10	19.751	1.050%	0.207	35%	5.12	6.58	10%	90%	1.463	13.167					**FA2**
19				23.80	32.91	19.751	1.050%	0.207	35%	5.12	6.58	20%	80%	2.926	11.704					**FA2**
20				23.80	32.73	19.751	1.050%	0.207	35%	5.12	6.58	30%	70%	4.389	10.241					**FA2**
21				23.80	32.54	19.751	1.050%	0.207	35%	5.12	6.58	40%	60%	5.852	8.778					**FA2**
22	35	14.63		23.80	32.98	19.751	1.050%	0.207	35%	5.12	6.58					30%	70%	4.389	10.241	**Slag**
23				23.80	32.89	19.751	1.050%	0.207	35%	5.12	6.58					40%	60%	5.852	8.778	**Slag**
24				23.80	32.79	19.751	1.050%	0.207	35%	5.12	6.58					50%	50%	7.315	7.315	**Slag**
25				23.80	32.69	19.751	1.050%	0.207	35%	5.12	6.58					60%	40%	8.778	5.852	**Slag**
26				23.80	32.59	19.751	1.050%	0.207	35%	5.12	6.58					70%	30%	10.241	4.389	**Slag**

Table A.2: Test results for C1 using SP1

Mix	Slump Flow				V-funnel	L-Box								Passing Ratio	Segregation ratio			
	X (mm)	Y (mm)	Ave	T_{500} (sec)	Tf (sec)	H1.1	H1.2	H1.3	H1	H2.1	H2.2	H2.3	H2	PA	Mass of Pan (WP)	Mass of Concrete (Wc)	Mass of Con& Pan (Wps)	SR
1	580	590	585	2.3	8.30	500	500	500	500	60	60	60	60	0.90	1.380	4.850	1.880	10.3%
2	690	680	685	2.0	4.70	500	500	500	500	60	60	60	60	0.90	1.380	4.960	2.770	28.0%
3	700	730	715	2.00	5.20	505	500	506	504	63	60	62	62	0.92	1.380	4.960	2.800	28.6%
4	670	670	670	1.90	5.90	502	505	505	504	60	60	58	59	0.94	1.380	4.960	2.770	28.0%
5	655	645	650	4.40	6.10	505	510	508	508	59	55	57	57	1.01	1.380	4.960	2.720	27.0%
6	730	740	735	1.60	4.80	505	505	500	503	59	60	59	59	0.94	1.380	4.860	2.720	27.6%
7	730	740	735	2.50	5.10	500	550	550	533	56	60	58	58	1.38	1.380	4.960	3.580	44.4%
8	750	760	755	2.30	5.90	500	500	500	500	60	60	60	60	0.90	1.380	4.940	4.300	59.1%
9	800	800	800	2.10	6.90	500	500	500	500	60	60	60	60	0.90	1.380	4.940	4.300	59.1%
10	630	640	635	1.70	4.53	510	515	513	513	55	60	58	58	1.06	1.380	5.020	4.180	55.8%
11	580	600	590	4.00	5.70	510	505	508	508	65	65	65	65	0.92	1.380	4.820	3.700	48.1%
12	715	670	692.5	2.40	5.20	500	500	500	500	60	60	60	60	0.90	1.380	4.820	2.120	15.4%
13	570	585	577.5	2.70	5.85	505	510	508	508	60	60	60	60	0.97	1.380	5.040	4.060	53.2%
14	820	830	825	1.80	7.20	500	500	500	500	60	60	60	60	0.90	1.040	2.370	1.960	38.8%
15	780	750	765	2.40	6.50	500	500	500	500	60	60	60	60	0.90	1.040	2.380	1.460	17.6%
16	780	750	765	2.20	7.30	500	500	500	500	60	60	60	60	0.90	1.040	2.420	1.620	24.0%
17	810	780	795	2.70	9.00	500	500	500	500	60	60	60	60	0.90	1.040	2.340	1.680	27.4%
18	735	710	722.5	2.16	4.65	500	505	510	505	55	60	60	58	0.96	1.380	4.840	3.340	40.5%
19	795	775	785	1.37	6.13	510	510	515	512	55	55	55	55	1.08	1.380	4.970	3.740	47.5%
20	880	850	865	0.90	5.84	510	510	510	510	55	55	55	55	1.06	1.380	5.040	4.920	70.2%
21	890	870	880	1.31	5.81	515	515	510	513	55	55	55	55	1.10	1.380	4.940	5.360	80.6%
			0															
22	900	900	900	1.40	50.1	500	500	500	500	60	60	60	60	0.90	1.380	4.920	4.860	70.7%
23	860	850	855	1.60	10.2	500	500	500	500	60	60	60	60	0.90	1.380	4.960	5.900	91.1%
24	880	880	880	1.60	8.4	500	500	500	500	60	60	60	60	0.90	1.380	5.020	6.120	94.4%
25	900	900	900	1.40	12.2	500	500	500	500	60	60	60	60	0.90	1.380	5.000	5.760	87.6%
26	900	900	900	1.70	29.3	500	500	500	500	60	60	60	60	0.90	1.380	4.800	6.000	96.3%

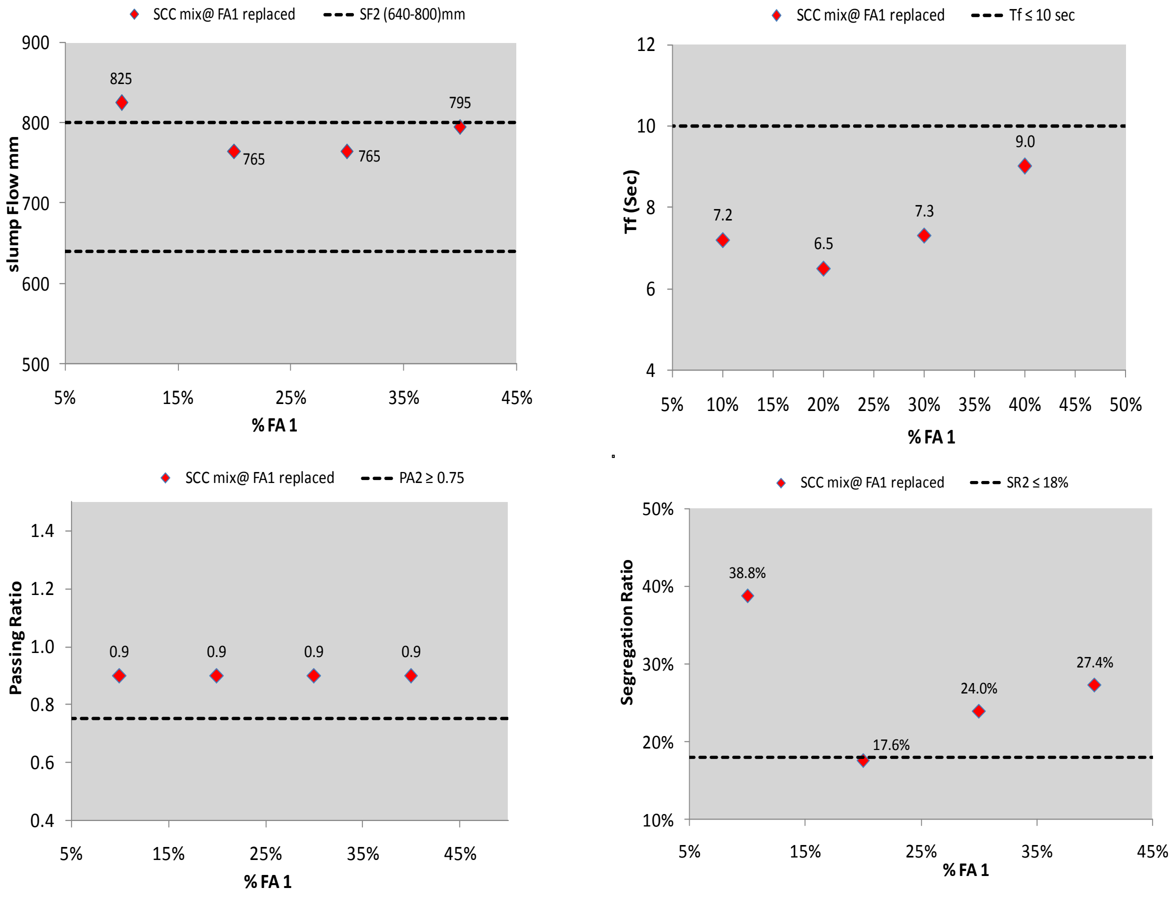

Figure A.1: Effect of replacing C1 with FA1 on SCC properties at sufficient SP1 concentration

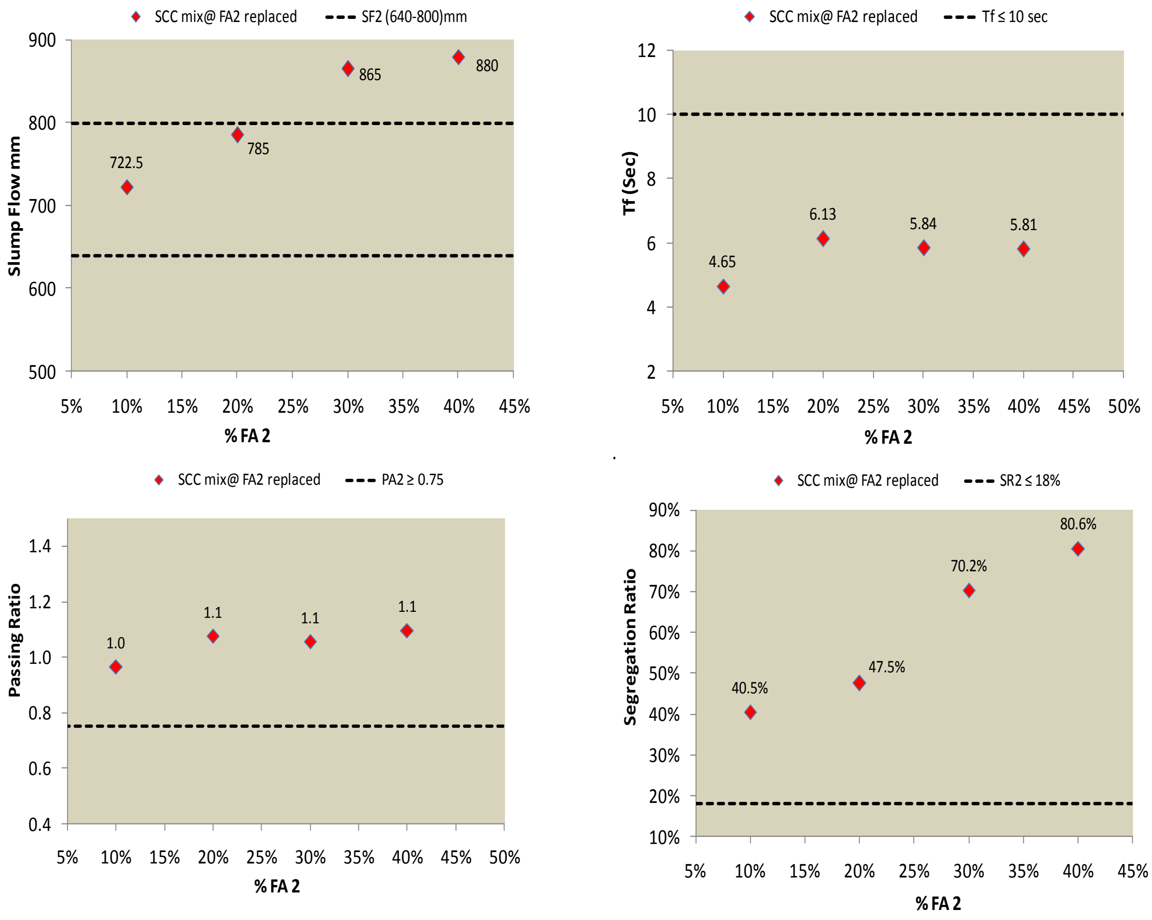

Figure A.2: Effect of replacing C1 with FA2 on SCC properties at sufficient SP1 concentration

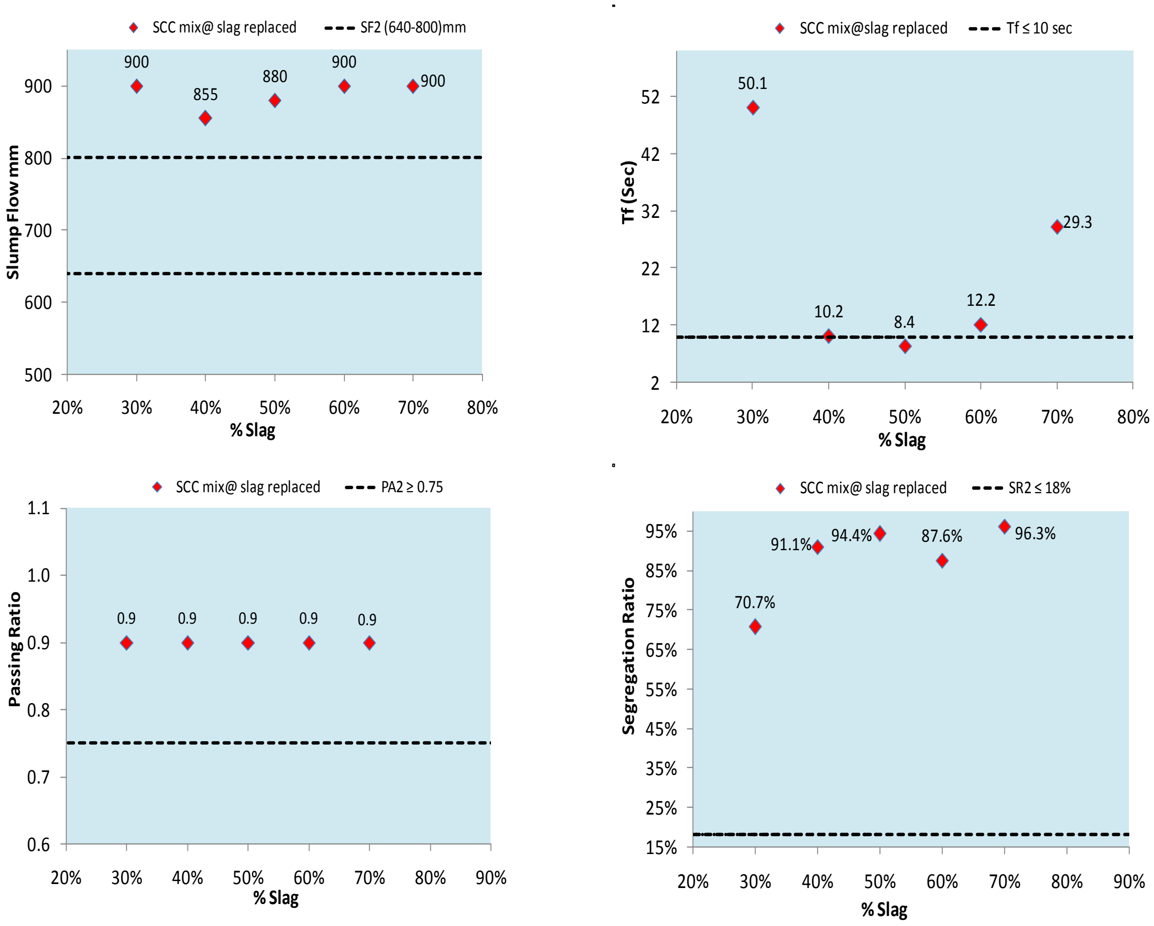

Figure A.3: Effect of replacing C1 with slag on SCC properties at sufficient SP1 concentration

Appendix B. (C2 with SP1)

- Table B.1: Mix proportions for C2 using SP1
- Table B.2: Test results for C2 using SP1
- Figure B.1: SCC property results relative to SP and limestone percentage using SP1 sufficient dosage on C2
- Figure B.2: Effect of replacing C2 with FA1 on SCC properties at sufficient SP1 concentration
- Figure B.3: Effect of replacing C2 with FA2 on SCC properties at sufficient SP1 concentration
- Figure B.4: Effect of replacing C2 with slag on SCC properties at sufficient SP1 concentration

Table B.1: Mix proportions for C2 using SP1

Mix	**Litre**	**Cementations kg**	**w/c**	**Stone kg**	**Sand kg**	**Fines kg**	**SP %**	**SP kg**	**CD %**	**CD kg**	**Water kg**	**FA / C %**		**Fly Ash kg**	**Cement kg**	**S / C %**		**Slag kg**	**Cement kg**	**Variables**
34	35	14.63		23.80	23.86	15.570	0.800%	0.113	35%	5.12	6.58		100%		10.450					**SP1**
35				23.80	23.81	15.570	0.950%	0.134	35%	5.12	6.58		100%		10.450					**SP1**
23				23.80	33.33	19.750	0.950%	0.188	35%	5.12	6.58		100%		14.630					**SP1**
38				23.80	23.80	15.570	0.975%	0.138	35%	5.12	6.58		100%		10.450					**SP1**
36				23.80	23.79	15.570	1.000%	0.141	35%	5.12	6.58		100%		10.450					**SP1**
26				23.80	33.30	19.750	1.000%	0.198	35%	5.12	6.58		100%		14.630					**SP1**
32				23.80	23.78	15.570	1.025%	0.145	35%	5.12	6.58		100%		10.450					**SP1**
33				23.80	23.28	15.570	1.025%	0.150	40%	5.12	6.58		100%		10.450					**SP1**
37				23.80	23.77	15.570	1.050%	0.148	35%	5.12	6.58		100%		10.450					**SP1**
24				23.80	33.28	19.750	1.050%	0.207	35%	5.12	6.58		100%		14.630					**SP1**
27				23.80	33.26	19.750	1.100%	0.217	35%	5.12	6.58		100%		14.630					**SP1**
25				23.80	33.23	19.750	1.150%	0.227	35%	5.12	6.58		100%		14.630					**SP1**
43	35	14.63		23.80	33.30	19.750	1.000%	0.198	25%	5.12	6.58		100%		14.630					**LM**
44				23.80	33.30	19.750	1.000%	0.198	30%	5.12	6.58		100%		14.630					**LM**
45				23.80	33.30	19.750	1.000%	0.198	35%	5.12	6.58		100%		14.630					**LM**
46				23.80	33.30	19.750	1.000%	0.198	40%	5.12	6.58		100%		14.630					**LM**
47	35	14.63		23.80	33.12	19.751	1.000%	0.198	35%	5.12	6.58	10%	90%	1.463	13.167					**FA1**
48				23.80	32.94	19.751	1.000%	0.198	35%	5.12	6.58	20%	80%	2.926	11.704					**FA1**
49				23.80	32.75	19.751	1.000%	0.198	35%	5.12	6.58	30%	70%	4.389	10.241					**FA1**
50				23.80	32.57	19.751	1.000%	0.198	35%	5.12	6.58	40%	60%	5.852	8.778					**FA1**
51	35	14.63		23.80	33.12	19.751	1.000%	0.198	35%	5.12	6.58	10%	90%	1.463	13.167					**FA2**
52				23.80	32.94	19.751	1.000%	0.198	35%	5.12	6.58	20%	80%	2.926	11.704					**FA2**
53				23.80	32.75	19.751	1.000%	0.198	35%	5.12	6.58	30%	70%	4.389	10.241					**FA2**
54				23.80	32.57	19.751	1.000%	0.198	35%	5.12	6.58	40%	60%	5.852	8.778					**FA2**
55	35	14.63		23.80	33.01	19.751	1.000%	0.198	35%	5.12	6.58					30%	70%	4.389	10.241	**Slag**
56				23.80	32.91	19.751	1.000%	0.198	35%	5.12	6.58					40%	60%	5.852	8.778	**Slag**
57				23.80	32.81	19.751	1.000%	0.198	35%	5.12	6.58					50%	50%	7.315	7.315	**Slag**
58				23.80	32.71	19.751	1.000%	0.198	35%	5.12	6.58					60%	40%	8.778	5.852	**Slag**
59				23.80	32.61	19.751	1.000%	0.198	35%	5.12	6.58					70%	30%	10.241	4.389	**Slag**

Table B.2: Test results for C2 using SP1

Mix	Slump Flow				V-funnel	L-Box								Passing Ratio	Segregation ratio			
	X (mm)	Y (mm)	Ave	T_{500}	Tf (sec)	H1.1	H1.2	H1.3	H1	H2.1	H2.2	H2.3	H2	PA	Mass of Pan (WP)	Mass of Concrete (Wc)	Mass of Con& Pan (Wps)	SR
34	370	390	380	1.40	10.5	485	490	480	485	75	70	75	73	0.67	1.38	5	1.38	0.00%
35	650	640	645	1.40	10.5	495	490	485	490	65	65	70	67	0.76	1.38	5.1	1.38	0.00%
23	650	625	637.5	2.5	7.8	500	505	520	508	60	60	60	60	0.98	1.38	5.1	1.38	0.00%
38	690	650	670	1.40	10.5	495	500	495	497	60	65	60	62	0.85	1.38	5.01	1.39	0.20%
36	740	730	735	1.40	10.5	485	490	480	485	75	70	75	73	0.67	1.38	4.84	1.56	3.72%
26	620	630	625	2.4	6.5	495	490	485	490	65	65	70	67	0.76	1.38	4.7	1.56	3.8%
32	790	760	775	1.4	10.5	500	505	520	508	60	60	60	60	0.98	1.38	5	1.8	8.4%
33	790	780	785	1.40	10.5	495	500	495	497	60	65	60	62	0.85	1.38	5	1.43	1.0%
37	790	770	780	1.40	10.5	485	490	480	485	75	70	75	73	0.67	1.38	5.16	1.64	5.0%
24	750	760	755	1.6	7.3	495	490	485	490	65	65	70	67	0.76	1.38	4.9	1.43	1.0%
27	790	780	785	1.5	7.9	500	505	520	508	60	60	60	60	0.98	1.38	4.88	1.43	1.0%
25	920	920	920	1.4	10.5	495	500	495	497	60	65	60	62	0.85	1.38	5	1.4	0.4%
43	665	650	657.5	2.0	7.8	485	490	480	485	75	70	75	73	0.67	1.38	4.820	1.386	0.1%
44	690	685	687.5	1.8	6.9	495	490	485	490	65	65	70	67	0.76	1.38	4.860	1.440	1.2%
45	730	725	727.5	1.3	6.0	500	505	520	508	60	60	60	60	0.98	1.38	4.820	1.480	2.1%
46	745	725	735	1.5	5.5	495	500	495	497	60	65	60	62	0.85	1.38	4.860	1.387	0.1%
47	525	510	517.5	4.0	15.0	390	400	345	378	145	145	145	145	0.02	1.38	4.900	1.383	0.1%
48	600	600	600	1.9	10.4	440	445	430	438	100	95	105	100	0.31	1.38	4.840	1.383	0.1%
49	590	545	567.5	1.9	12.3	450	450	435	445	95	100	105	100	0.32	1.38	4.840	1.385	0.1%
50	590	590	590	1.4	15.0	440	450	440	443	105	100	105	103	0.30	1.38	4.900	1.387	0.1%
51	630	620	625	2.0	7.5	460	460	460	460	100	100	100	100	0.36	1.38	4.920	1.380	0.0%
52	720	705	712.5	1.2	6.3	485	485	490	487	75	75	75	75	0.66	1.38	4.860	1.820	9.1%
53	700	675	687.5	1.4	5.3	495	490	485	490	75	75	70	73	0.70	1.38	4.860	1.600	4.5%
54	765	745	755	1.1	4.4	490	490	485	488	75	75	75	75	0.67	1.38	4.900	1.600	4.5%
55	645	635	640	2.4	5.9	490	490	490	490	75	75	75	75	0.68	1.38	4.940	1.580	4.0%
56	715	725	720	1.5	6.6	490	490	500	493	70	70	65	68	0.77	1.38	4.840	1.395	0.3%
57	670	700	685	1.7	4.8	485	485	485	485	65	65	65	65	0.74	1.38	4.790	1.510	2.7%
58	840	800	820	1.6	5.8	500	500	500	500	60	60	60	60	0.90	1.38	4.940	2.157	15.7%
59	850	900	875	1.2	6.3	500	500	500	500	60	60	60	60	0.90	1.38	4.900	5.257	79.1%

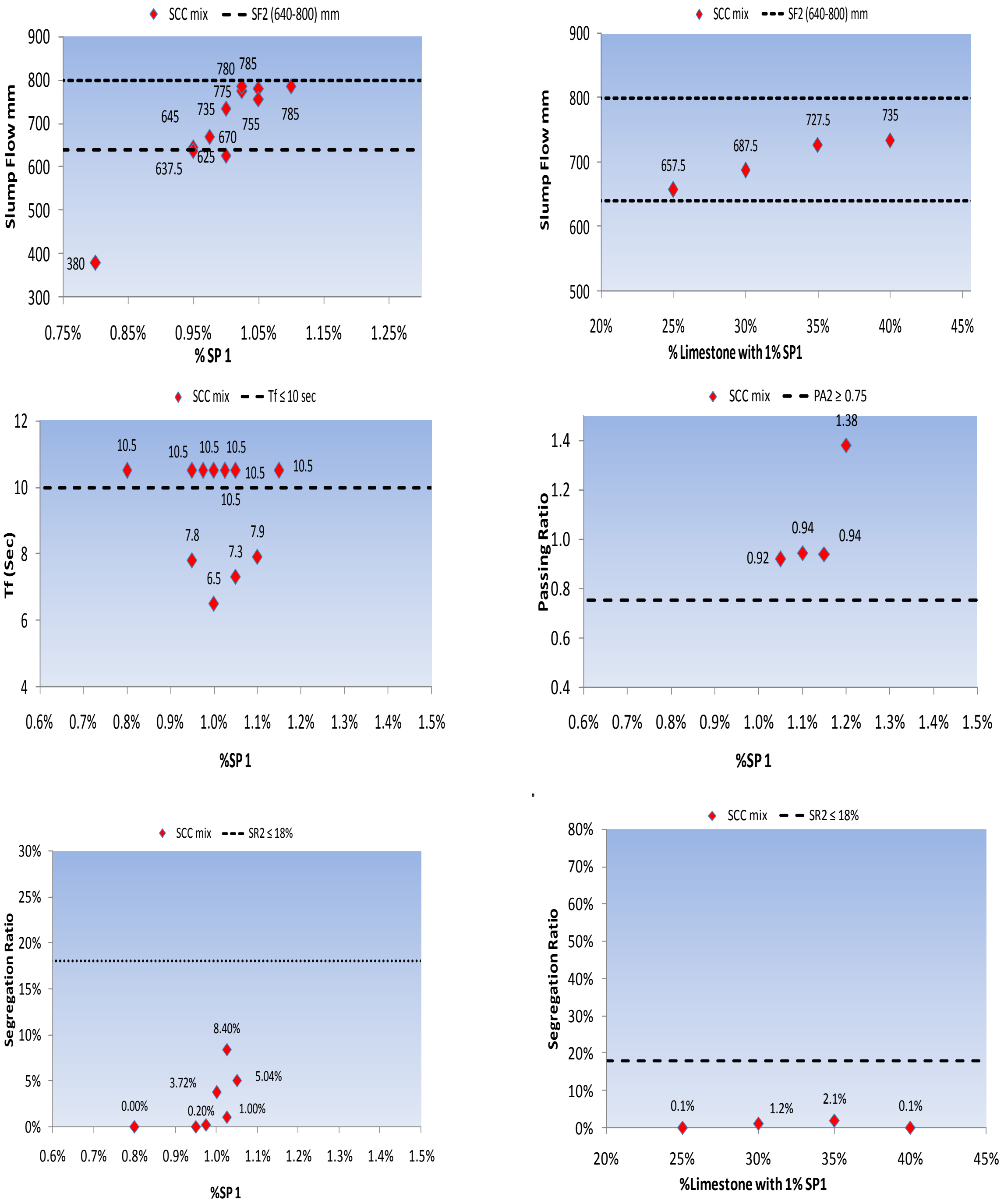

Figure B.1: SCC property results relative to SP and limestone percentage using SP1 sufficient dosage on C2

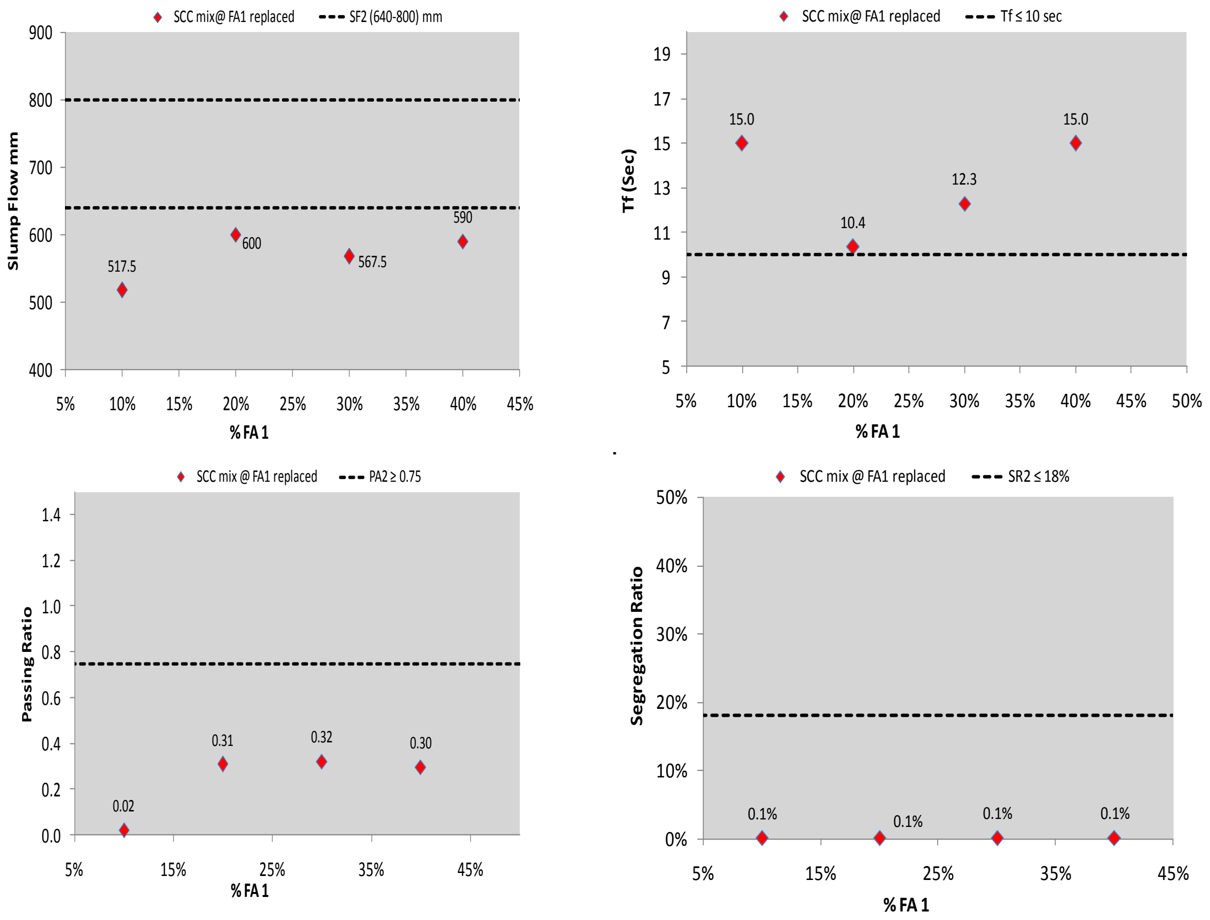

Figure B.2: Effect of replacing C2 with FA1 on SCC properties at sufficient SP1 concentration

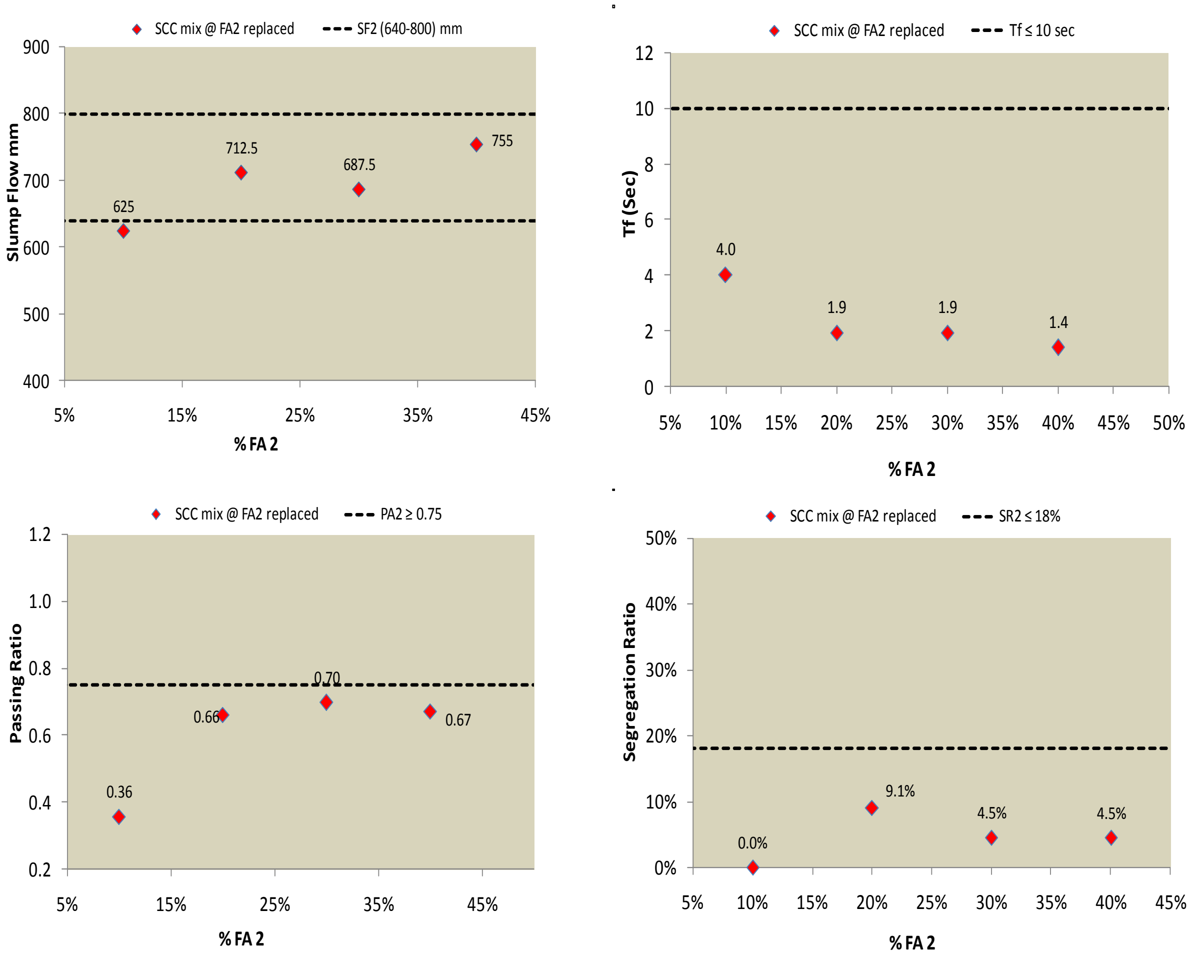

Figure B.3: Effect of replacing C2 with FA2 on SCC properties at sufficient SP1 concentration

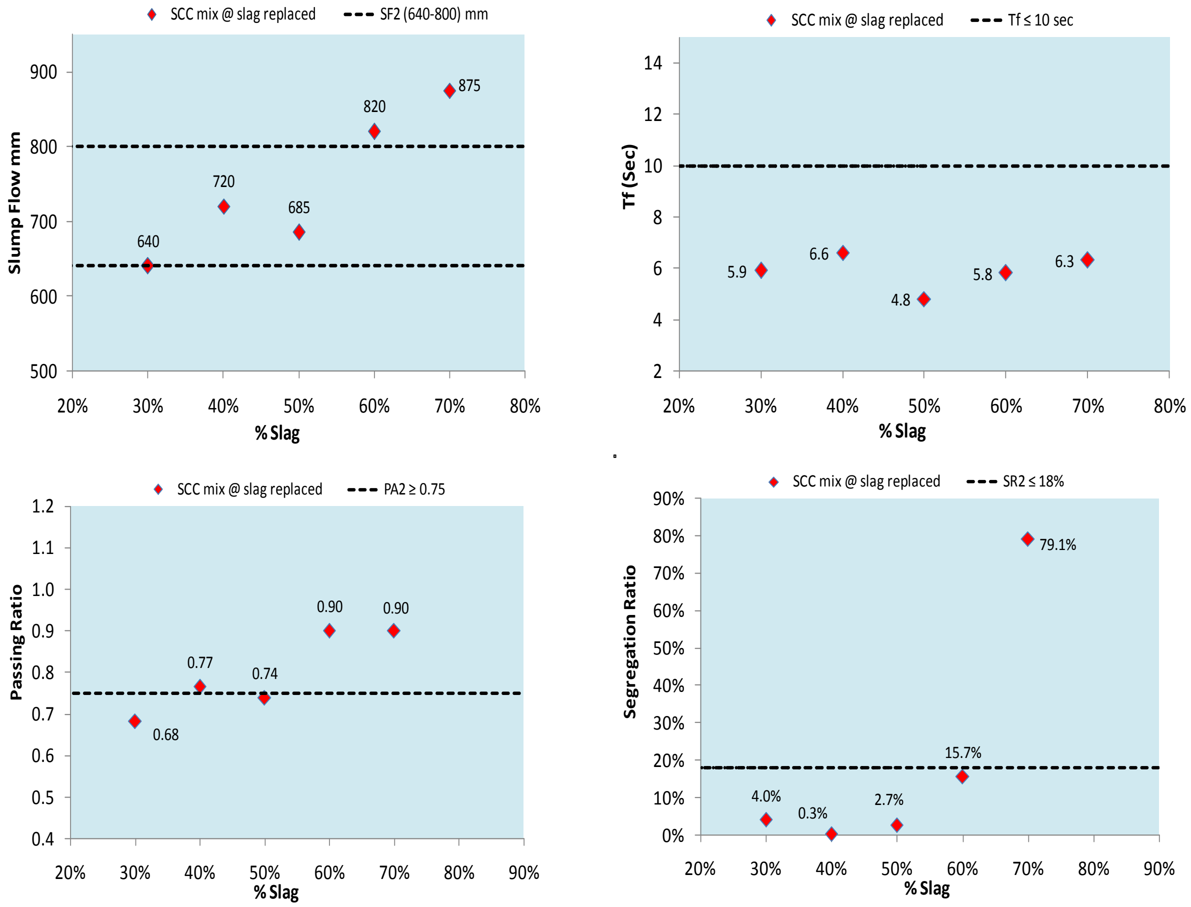

Figure B.4: Effect of replacing C2 with slag on SCC properties at sufficient SP1 concentration

Appendix C. (C3 with SP1)

- Table C.1: Mix proportions for C3 using SP1
- Table C.2: Test results for C3 using SP1
- Figure C.1: SCC property results relative to SP and limestone percentage using SP1 sufficient dosage on C3
- Figure C.2: Effect of replacing C3 with FA1 on SCC properties at sufficient SP1 concentration
- Figure C.3: Effect of replacing C3 with FA2 on SCC properties at sufficient SP1 concentration
- Figure C.4: Effect of replacing C3 with slag on SCC properties at sufficient SP1 concentration

Table C.1: Mix proportions for C3 using SP1

Mix	Litre	Cementations kg	w/c	Stone kg	Sand kg	Fines kg	SP %	SP kg	CD %	CD kg	Water kg	FA / C %		Fly Ash kg	Cement kg	S / C %		Slag kg	Cement kg	
60	35	14.63		23.80	33.43	19.751	0.740%	0.146	35%	5.12	6.58		100%		14.630					**SP1**
61				23.80	33.35	19.751	0.900%	0.178	35%	5.12	6.58		100%		14.630					**SP1**
62				23.80	33.33	19.751	0.950%	0.188	35%	5.12	6.58		100%		14.630					**SP1**
63				23.80	33.30	19.751	1.000%	0.198	35%	5.12	6.58		100%		14.630					**SP1**
64				23.80	33.28	19.751	1.050%	0.207	35%	5.12	6.58		100%		14.630					**SP1**
65				23.80	33.26	19.751	1.100%	0.217	35%	5.12	6.58		100%		14.630					**SP1**
66				23.80	33.23	19.751	1.150%	0.227	35%	5.12	6.58		100%		14.630					**SP1**
67				23.80	33.08	19.751	1.480%	0.292	35%	5.12	6.58		100%		14.630					**SP1**
68	35	14.63		23.80	34.69	18.288	1.050%	0.192	25%	3.66	6.58		100%		14.630					**LM**
69				23.80	33.99	19.019	1.050%	0.200	30%	4.39	6.58		100%		14.630					**LM**
70				23.80	33.28	19.751	1.050%	0.207	35%	5.12	6.58		100%		14.630					**LM**
71				23.80	32.57	20.482	1.050%	0.215	40%	5.85	6.58		100%		14.630					**LM**
72	35	14.63		23.80	34.51	18.288	1.050%	0.192	25%	3.66	6.58	10%	90%	1.463	13.167					**FA1**
73				23.80	34.33	18.288	1.050%	0.192	25%	3.66	6.58	20%	80%	2.926	11.704					**FA1**
74				23.80	34.14	18.288	1.050%	0.192	25%	3.66	6.58	30%	70%	4.389	10.241					**FA1**
75				23.80	33.96	18.288	1.050%	0.192	25%	3.66	6.58	40%	60%	5.852	8.778					**FA1**
76	35	14.63		23.80	34.51	18.288	1.050%	0.192	25%	3.66	6.58	10%	90%	1.463	13.167					**FA2**
77				23.80	34.33	18.288	1.050%	0.192	25%	3.66	6.58	20%	80%	2.926	11.704					**FA2**
78				23.80	34.14	18.288	1.050%	0.192	25%	3.66	6.58	30%	70%	4.389	10.241					**FA2**
79				23.80	33.96	18.288	1.050%	0.192	25%	3.66	6.58	40%	60%	5.852	8.778					**FA2**
80	35	14.63		23.80	34.40	18.288	1.050%	0.192	25%	3.66	6.58					30%	70%	4.389	10.241	**Slag**
81				23.80	34.30	18.288	1.050%	0.192	25%	3.66	6.58					40%	60%	5.852	8.778	**Slag**
82				23.80	34.20	18.288	1.050%	0.192	25%	3.66	6.58					50%	50%	7.315	7.315	**Slag**
83				23.80	34.10	18.288	1.050%	0.192	25%	3.66	6.58					60%	40%	8.778	5.852	**Slag**
84				23.80	34.00	18.288	1.050%	0.192	25%	3.66	6.58					70%	30%	10.241	4.389	**Slag**

Table C.2: Test results for C3 using SP1

Mix	Slump Flow				V-funnel	L-Box								Passing Ratio	Segregation ratio			
	X (mm)	Y (mm)	Ave	T 500 (sec)	Tf (sec)	H1.1	H1.2	H1.3	H1	H2.1	H2.2	H2.3	H2	PA	Mass of Pan (WP)	Mass of Concrete (Wc)	Mass of Con& Pan (Wps)	SR
60	600	570	585	0.3	6.60	450	500	455	468	60	80	90	77	0.56	1.380	5.000	1.600	4.4%
61	600	570	585	1.3	6.60	450	460	455	455	90	90	90	90	0.41	1.380	4.840	1.500	2.5%
62	530	530	530	2.96	6.41	450	480	500	477	90	90	90	90	0.49	1.380	4.900	1.440	1.2%
63	640	615	627.5	1.40	5.60	450	460	455	455	90	90	88	89	0.42	1.380	4.740	1.540	3.4%
64	755	725	740	1.23	4.72	450	460	455	455	90	90	90	90	0.41	1.380	4.920	1.790	8.3%
65	715	705	710	1.38	4.44	500	460	500	487	85	85	85	85	0.57	1.380	4.720	1.650	5.7%
66	770	750	760	1.38	4.68	450	460	455	455	90	90	90	90	0.41	1.380	4.780	2.190	16.9%
67	800	750	775	1.38	4.68	480	500	480	487	90	90	90	90	0.53	1.380	4.780	2.210	17.4%
68	700	720	710	1.70	5.00	450	460	455	455	90	90	90	90	0.41	1.380	4.860	1.740	7.4%
69	670	710	690	2.10	5.10	450	460	455	455	90	90	90	90	0.41	1.380	4.940	1.660	5.7%
70	620	635	627.5	1.90	5.25	450	460	455	455	90	90	90	90	0.41	1.380	4.900	1.660	5.7%
71	630	660	645	2.20	5.70	450	460	455	455	90	90	90	90	0.41	1.380	4.780	1.550	3.6%
72	520	560	540	2.06	5.20	450	460	455	455	90	90	90	90	0.41	1.380	4.720	1.441	1.3%
73	605	600	602.5	2.03	6.00	480	480	475	478	70	75	75	73	0.63	1.380	4.820	1.380	1.4%
74	595	615	605	2.22	7.10	500	500	500	500	60	60	60	60	0.90	1.380	5.200	1.520	2.7%
75	755	750	752.5	2.25	7.70	495	495	495	495	60	60	60	60	0.86	1.380	4.840	1.380	0.0%
76	670	640	655	1.90	4.20	500	500	500	500	60	60	60	60	0.90	1.380	4.900	1.640	5.3%
77	730	720	725	1.70	3.70	500	500	500	500	60	60	60	60	0.90	1.380	4.900	2.030	13.3%
78	720	700	710	1.20	3.50	500	500	500	500	60	60	60	60	0.90	1.380	5.070	2.540	22.9%
79	840	800	820	1.20	5.40	500	500	500	500	60	60	60	60	0.90	1.380	4.930	3.260	38.1%
			0															
80	780	780	780	1.60	3.5	500	500	500	500	60	60	60	60	0.90	1.380	4.910	2.910	31.2%
81	750	735	742.5	1.75	4.1	500	500	500	500	60	60	60	60	0.90	1.380	4.960	3.070	34.1%
82	800	775	787.5	1.44	4.1	500	500	500	500	60	60	60	60	0.90	1.380	5.010	3.970	51.7%
83	780	735	757.5	2.34	4.8	500	500	500	500	60	60	60	60	0.90	1.380	4.820	2.710	27.6%
84	840	835	837.5	1.55	5.5	500	500	500	500	60	60	60	60	0.90	1.380	4.820	4.030	55.0%

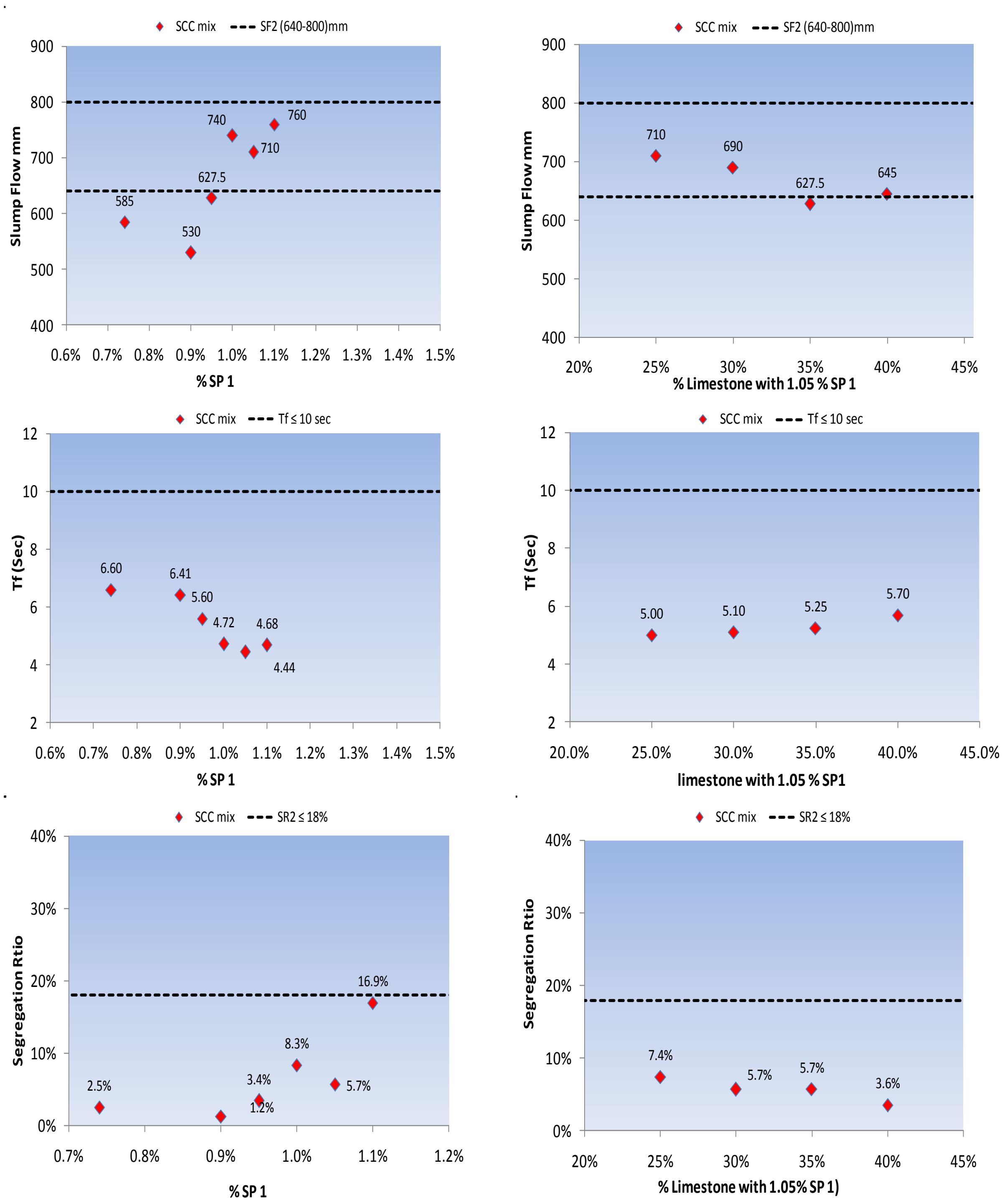

Figure C.1: SCC property results relative to SP and limestone percentage using SP1 optimum dosage on C3

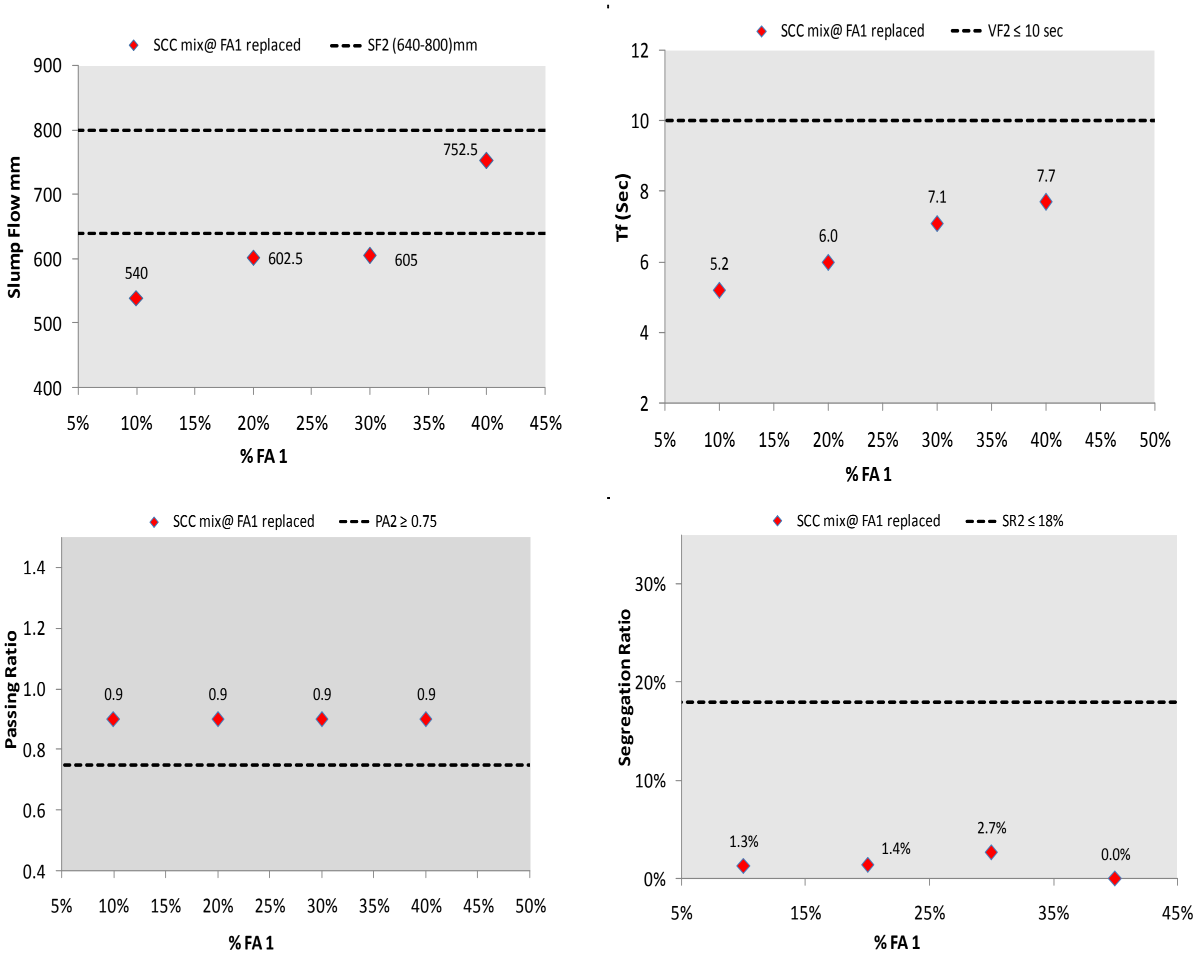

Figure C.2: Effect of replacing C3 with FA1 on SCC properties at sufficient SP1 concentration

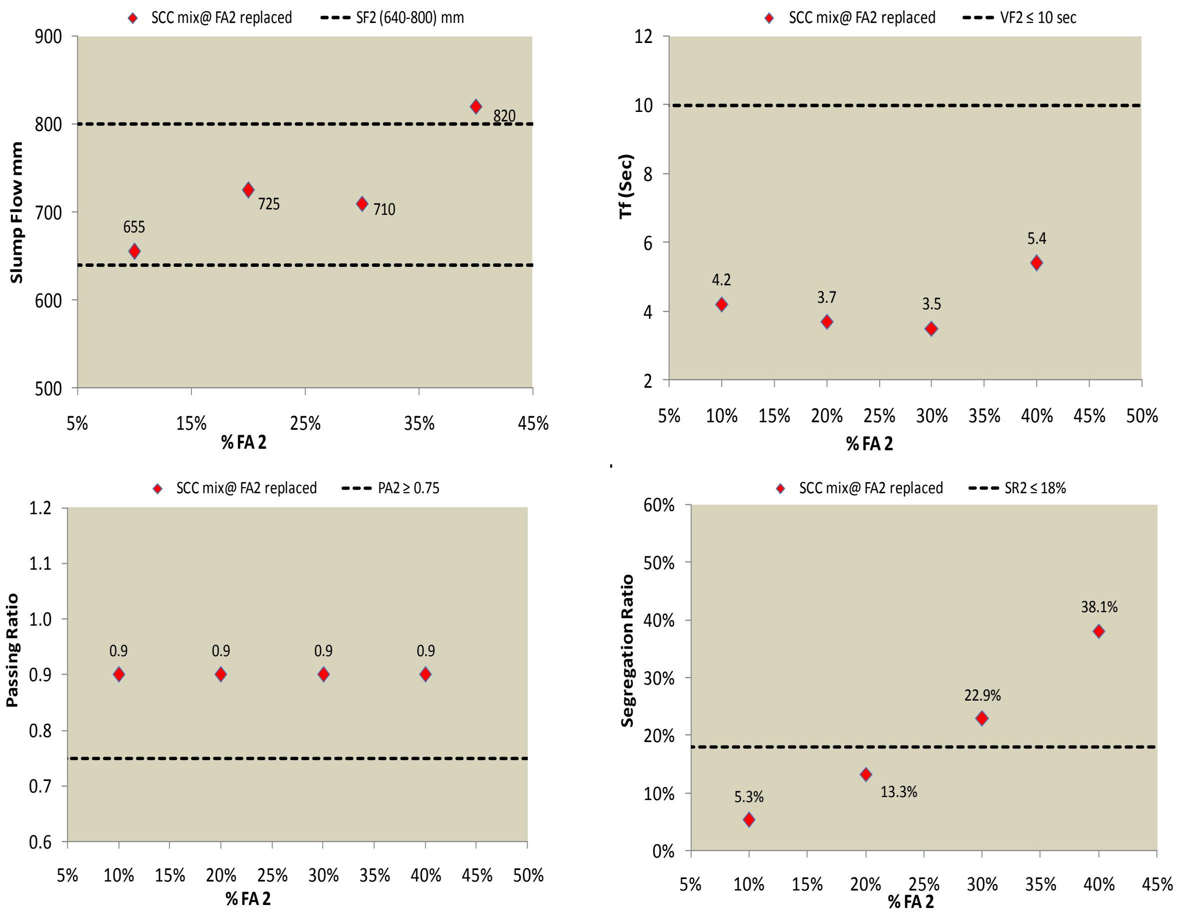

Figure C.3: Effect of replacing C3 with FA2 on SCC properties at sufficient SP1 concentration

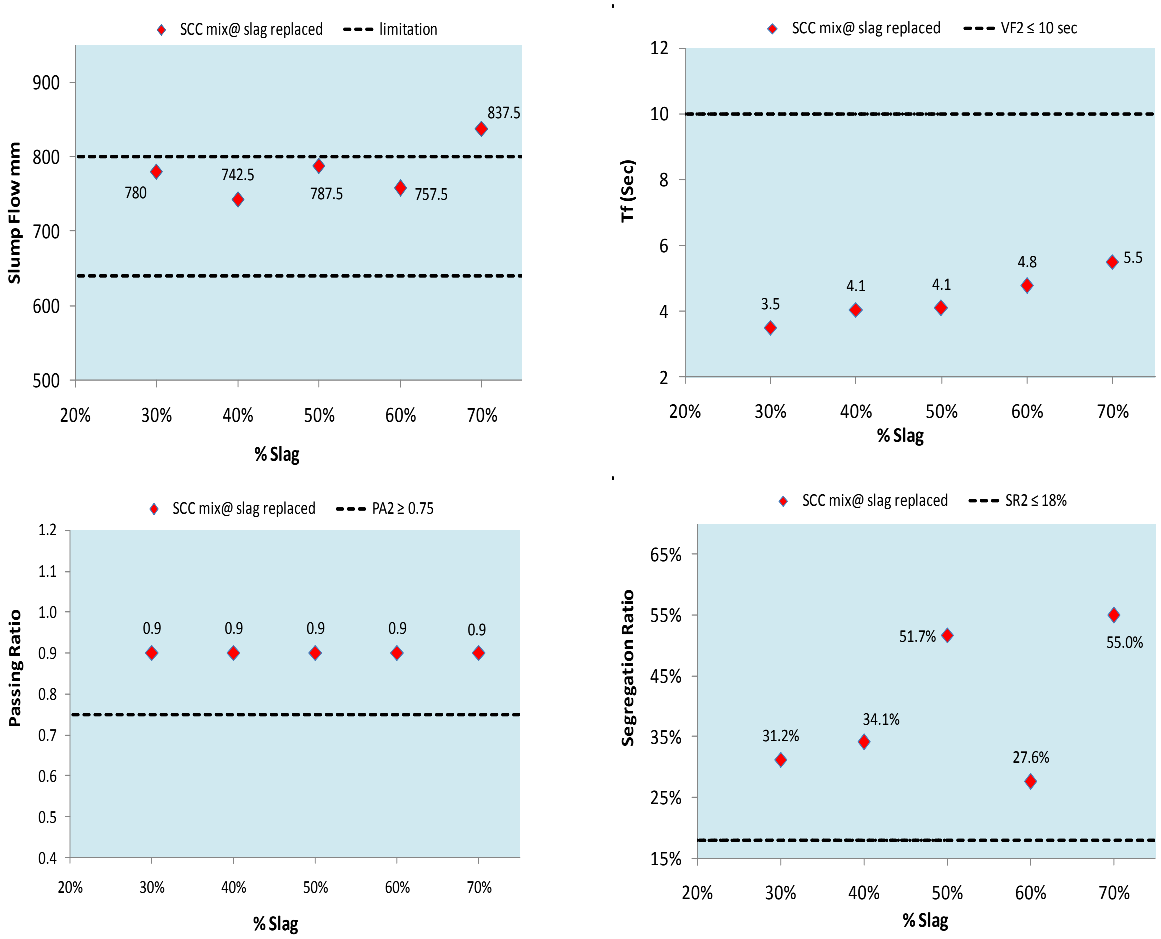

Figure C.4: Effect of replacing C3 with slag on SCC properties at sufficient SP1 concentration

Appendix D. (C4 with SP1)

- Table D.1: Mix proportions for C4 using SP1
- Table D.2: Test results for C4 using SP1
- Figure D.1: SCC property results relative to SP and limestone percentage using SP1 sufficient dosage on C4
- Figure D.2: Effect of replacing C4 with FA1 on SCC properties at sufficient SP1 concentration
- Figure D.3: Effect of replacing C4 with FA2 on SCC properties at sufficient SP1 concentration
- Figure D.4: Effect of replacing C4 with slag on SCC properties at sufficient SP1 concentration

Table D.1: Mix proportions for C4 using SP1

Mix	**Litre**	**Cementations kg**	**w/c**	**Stone kg**	**Sand kg**	**Fines kg**	**SP %**	**SP kg**	**CD %**	**CD kg**	**Water kg**	**FA / C %**		**Fly Ash kg**	**Cement kg**	**S / C %**		**Slag kg**	**Cement kg**	**Variables**
90	35	14.63		23.80	39.61	18.288	0.800%	0.146	25%	3.66	4.70		100%		14.630					**SP1**
91				23.80	39.59	18.288	0.850%	0.155	25%	3.66	4.70		100%		14.630					SP1
92				23.80	39.57	18.288	0.900%	0.165	25%	3.66	4.70		100%		14.630					**SP1**
93				23.80	39.55	18.288	0.950%	0.174	25%	3.66	4.70		100%		14.630					SP1
94				23.80	39.53	18.288	1.000%	0.183	25%	3.66	4.70		100%		14.630					**SP1**
95				23.80	39.51	18.288	1.050%	0.192	25%	3.66	4.70		100%		14.630					SP1
96				23.80	39.48	18.288	1.100%	0.201	25%	3.66	4.70		100%		14.630					**SP1**
97				23.80	39.46	18.288	1.150%	0.210	25%	3.66	4.70		100%		14.630					SP1
98				23.80	39.44	18.288	1.200%	0.219	25%	3.66	4.70		100%		14.630					**SP1**
99				23.80	39.42	18.288	1.250%	0.229	25%	3.66	4.70		100%		14.630					SP1
100				23.80	39.40	18.288	1.300%	0.238	25%	3.66	4.70		100%		14.630					**SP1**
101	35	14.63		23.80	38.89	18.288	1.200%	0.219	25%	3.66	4.70	30%	70%	4.389	10.241					**LM**
102				23.80	38.00	19.019	1.200%	0.228	30%	4.39	4.70	40%	60%	5.852	8.778					**LM**
103				23.80	37.10	19.751	1.200%	0.237	35%	5.12	4.70	50%	50%	7.315	7.315					**LM**
104				23.80	36.21	20.482	1.200%	0.246	40%	5.85	4.70	60%	40%	8.778	5.852					**LM**
105	35	14.63		23.80	34.44	18.288	1.200%	0.219	25%	3.66	6.58	10%	90%	1.463	13.167					**FA1**
106				23.80	34.26	18.288	1.200%	0.219	25%	3.66	6.58	20%	80%	2.926	11.704					**FA1**
107				23.80	34.08	18.288	1.200%	0.219	25%	3.66	6.58	30%	70%	4.389	10.241					**FA1**
108				23.80	33.89	18.288	1.200%	0.219	25%	3.66	6.58	40%	60%	5.852	8.778					**FA1**
									25%											
109	35	14.63		23.80	34.44	18.288	1.200%	0.219	25%	3.66	6.58	10%	90%	1.463	13.167					**FA2**
110				23.80	34.26	18.288	1.200%	0.219	25%	3.66	6.58	20%	80%	2.926	11.704					**FA2**
111				23.80	34.08	18.288	1.200%	0.219	25%	3.66	6.58	30%	70%	4.389	10.241					**FA2**
112				23.80	33.89	18.288	1.200%	0.219	25%	3.66	6.58	40%	60%	5.852	8.778					**FA2**
									25%											
113	35	14.63		23.80	34.33	18.288	1.200%	0.219	25%	3.66	6.58					30%	70%	4.389	10.241	**Slag**
114				23.80	34.23	18.288	1.200%	0.219	25%	3.66	6.58					40%	60%	5.852	8.778	**Slag**
115				23.80	34.13	18.288	1.200%	0.219	25%	3.66	6.58					50%	50%	7.315	7.315	**Slag**
116				23.80	34.04	18.288	1.200%	0.219	25%	3.66	6.58					60%	40%	8.778	5.852	**Slag**
117				23.80	33.94	18.288	1.200%	0.219	25%	3.66	6.58					70%	30%	10.241	4.389	**Slag**

Table D.2: Test results for C4 using SP1

	Slump Flow				**V-funnel**	**L-Box**							**Segregation ratio**			
Mix	X (mm)	Y (mm)	Ave	T500 (sec)	Tf (sec)	H1.1	H1.2	H1	H2.1	H2.2	H2	passing ratio	Mass Sieve	Mass of Con	Lift sieve and record mass	SR
90	450	460	455	2.3	8.30	490	500	495	55	55	55	0.90	1.38	4.82	1.38	0.0%
91	480	485	482.5	2.0	8.70	490	500	495	55	55	55	0.90	1.38	4.9	1.38	0.0%
92	510	510	510	2.00	5.20	490	500	495	55	55	55	0.90	1.38	4.85	1.38	0.0%
93	555	600	577.5	1.90	5.90	490	500	495	55	55	55	0.90	1.38	4.9	1.38	0.0%
94	590	570	580	4.40	6.10	490	500	495	55	55	55	0.90	1.38	4.88	1.38	0.0%
95	590	600	595	1.60	4.80	490	500	495	55	55	55	0.90	1.38	4.82	1.38	0.0%
96	565	600	582.5	2.50	5.00	490	500	495	55	55	55	0.90	1.38	4.9	1.45	1.4%
97	680	650	665	2.30	5.90	490	500	495	55	55	55	0.90	1.38	5.2	1.42	0.8%
98	735	710	722.5	2.10	6.90	490	500	495	55	55	55	0.90	1.38	4.92	1.66	5.7%
99	800	790	795	1.4	6.8	490	500	495	55	55	55	0.90	1.38	4.92	1.52	2.8%
100	860	820	840	1.1	5.3	490	500	495	55	55	55	0.90	1.38	5.18	1.5	2.3%
101	735	710	722.5	2.10	6.90	490	500	495	55	55	55	0.90	1.38	4.92	1.66	5.7%
102	670	680	675	1.36	7.1	490	500	495	55	55	55	0.90	1.38	4.82	1.52	2.9%
103	580	630	605	1.38	6.8	490	500	495	55	55	55	0.90	1.38	4.9	1.4	0.4%
104	520	510	515	1.06	8.3	490	500	495	55	55	55	0.90	1.38	4.8	1.4	0.4%
105	740	750	745	1.69	7.6	490	500	495	55	55	55	0.90	1.380	4.800	1.900	10.8%
106	850	830	840	1.40	7.7	500	500	500	60	60	60	0.90	1.380	5.080	3.380	39.4%
107	835	840	837.5	1.30	8.5	500	500	500	60	60	60	0.90	1.380	4.860	4.100	56.0%
108	825	830	827.5	1.10	7.7	500	500	500	60	60	60	0.90	1.380	5.020	4.200	56.2%
109	750	725	737.5	1.31	3.97	500	500	500	60	60	60	0.90	1.380	5.080	2.700	26.0%
110	900	880	890	0.9	4.00	500	500	500	60	60	60	0.90	1.380	5.040	4.400	59.9%
111	880	900	890	0.6	6.18	500	500	500	60	60	60	0.90	1.380	4.880	5.580	86.1%
112	900	900	900	0.6	10.10	500	500	500	60	60	60	0.90	1.380	4.880	5.700	88.5%
113	900	850	875	0.8	6.9	500	500	500	60	60	60	0.90	1.380	5.000	3.360	39.6%
114	810	835	822.5	1	4.3	500	500	500	60	60	60	0.90	1.380	4.900	2.960	32.2%
115	895	860	877.5	1.3	5.6	500	500	500	60	60	60	0.90	1.380	4.820	3.260	39.0%
116	900	890	895	1.13	10.6	500	500	500	60	60	60	0.90	1.380	4.920	4.100	55.3%
117	900	900	900	1.2	9.6	500	500	500	60	60	60	0.90	1.380	5.100	4.800	67.1%

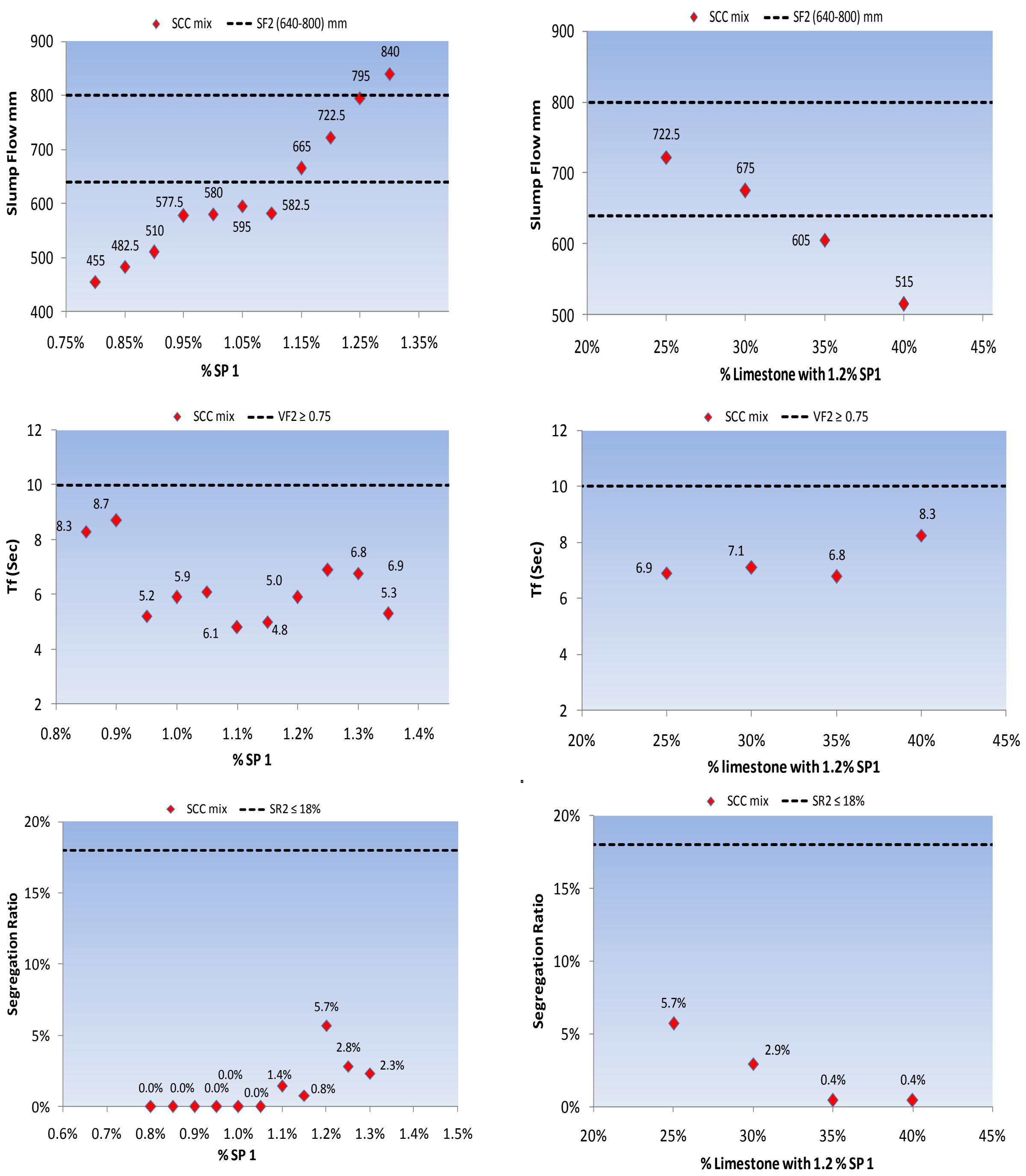

Figure D.1: SCC property results relative to SP and limestone percentage using SP1 optimum dosage on C4

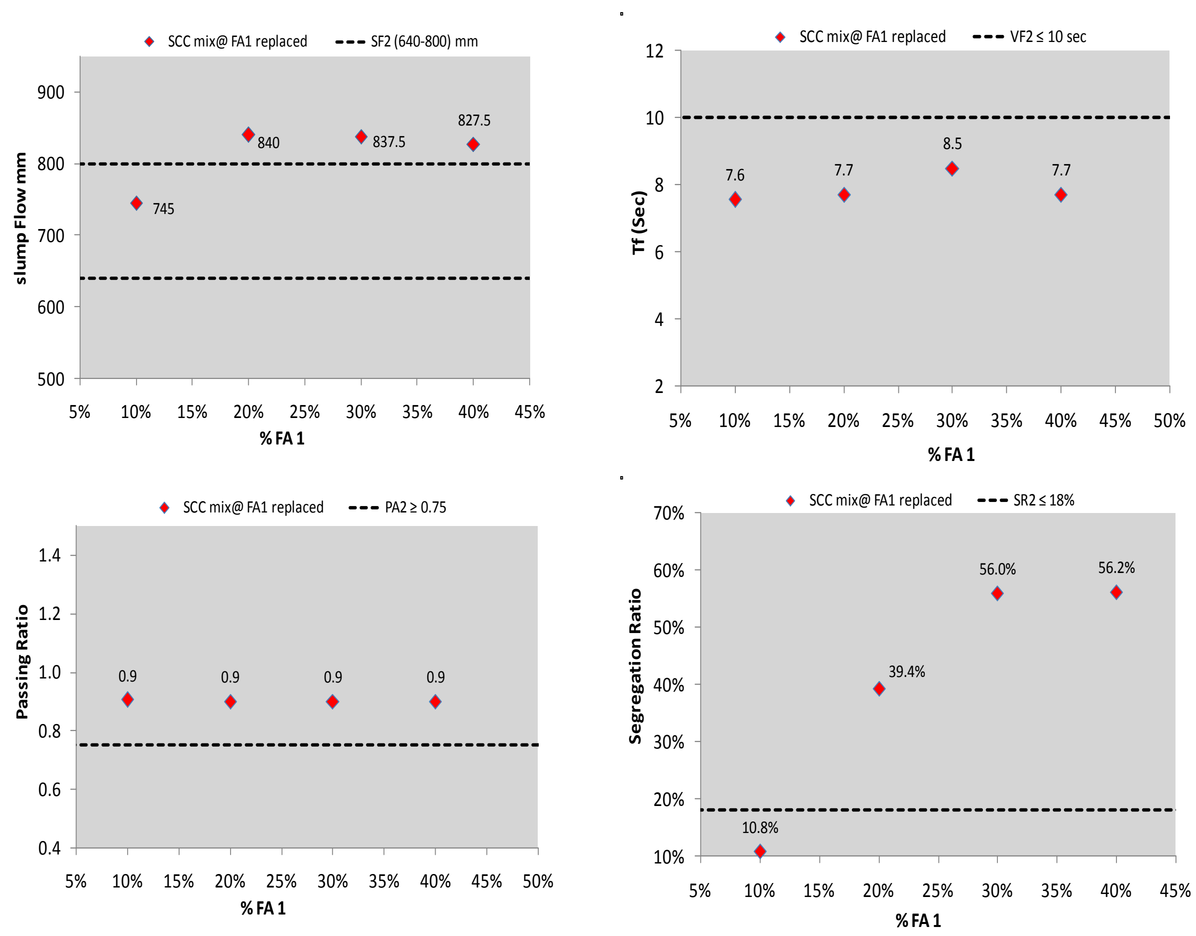

Figure D.2: Effect of replacing C4 with FA1 on SCC properties at sufficient SP1 concentration

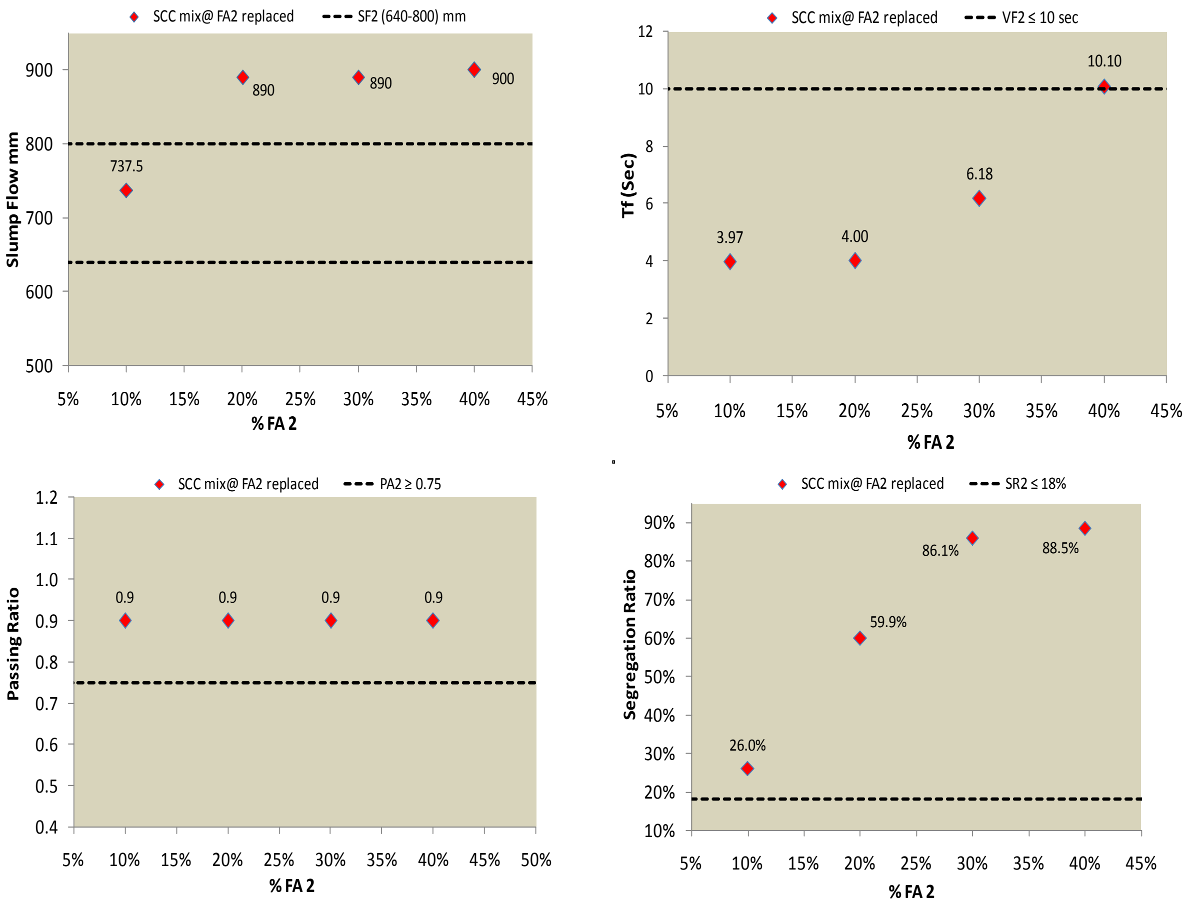

Figure D.3: Effect of replacing C4 with FA2 on SCC properties at sufficient SP1 concentration

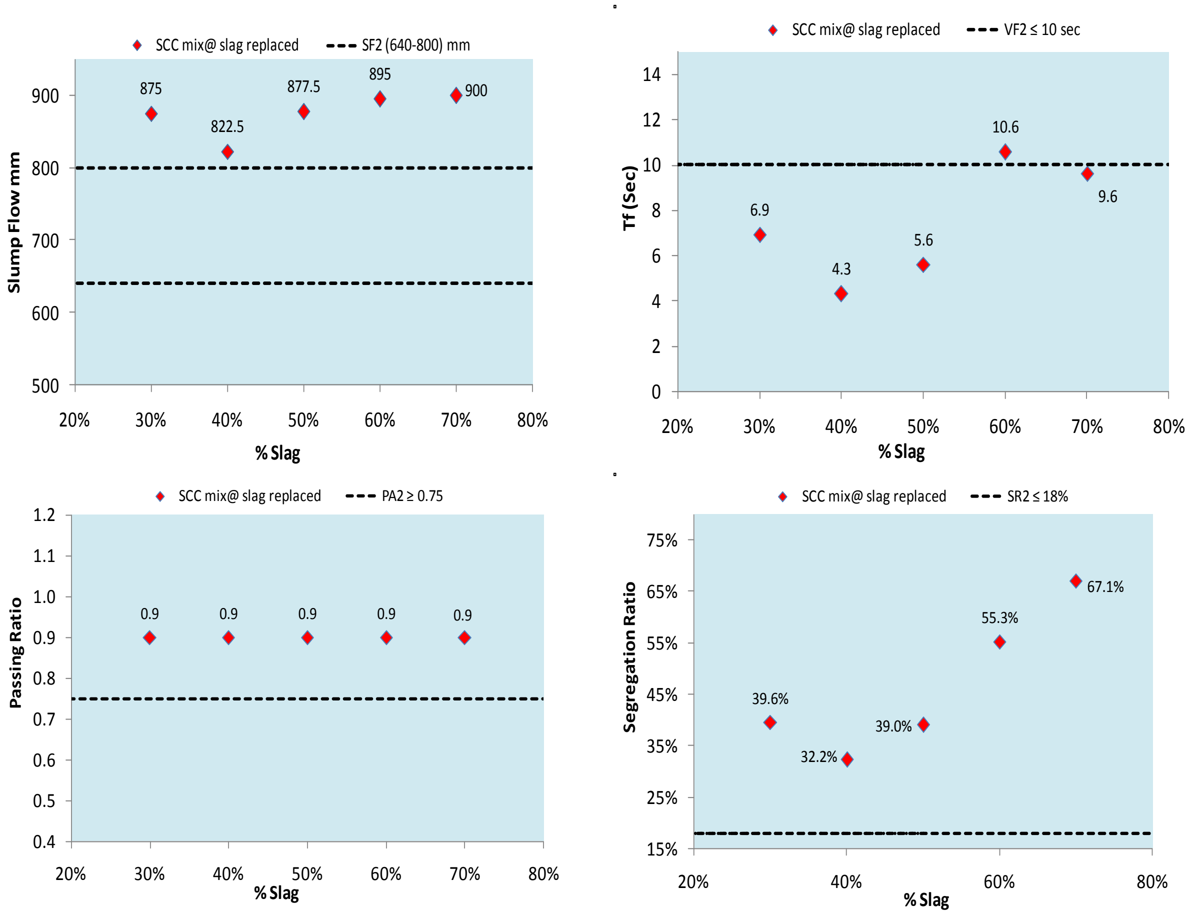

Figure D.4: Effect of replacing C4 with FA2 on SCC properties at sufficient SP1 concentration

Appendix E. (C1 with SP2)

- Table E.1: Mix proportions for C1 using SP2
- Table E.2: Test results for C1 using SP2
- Figure E.1: SCC property results relative to SP and limestone percentage using SP2 sufficient dosage on C1
- Figure E.2: Effect of replacing C1 with FA1 on SCC properties at sufficient SP2 concentration
- Figure E.3: Effect of replacing C1 with FA2 on SCC properties at sufficient SP2 concentration
- Figure E.4: Effect of replacing C1 with slag on SCC properties at sufficient SP2 concentration

Table E.1: Mix proportions for C1 using SP2

Mix	Litre	Cementations kg	w/c	Stone kg	Sand kg	Fines kg	SP %	SP kg	CD %	CD kg	Water kg	FA / C %		Fly Ash kg	Cement kg	S / C %		Slag kg	Cement kg	Variables
1	35	14.63		23.80	38.99	18.288	2.800%	0.410	25%	3.66	4.70	0%	100%		14.630					**SP2**
2				17.00	45.31	18.288	2.900%	0.424	25%	3.66	4.70	0%	100%		14.630					**SP2**
3				17.00	45.27	18.288	3.000%	0.439	25%	3.66	4.70	0%	100%		14.630					**SP2**
4				17.00	45.24	18.288	3.100%	0.454	25%	3.66	4.70	0%	100%		14.630					**SP2**
5				17.00	45.21	18.288	3.200%	0.468	25%	3.66	4.70	0%	100%		14.630					**SP2**
6				17.00	45.17	18.288	3.300%	0.483	25%	3.66	4.70	0%	100%		14.630					**SP2**
7				17.00	45.14	18.288	3.400%	0.497	25%	3.66	4.70	0%	100%		14.630					**SP2**
8				17.00	45.10	18.288	3.500%	0.512	25%	3.66	4.70	0%	100%		14.630					**SP2**
9	35	14.63		17.00	45.14	18.288	3.400%	0.497	25%	3.66	4.70	0%	100%		14.630					**LM**
10				17.00	44.45	19.019	3.400%	0.497	30%	4.39	4.70	0%	100%		14.630					**LM**
11				17.00	43.76	19.751	3.400%	0.497	35%	5.12	4.70	0%	100%		14.630					**LM**
12				17.00	43.07	20.482	3.400%	0.497	40%	5.85	4.70	0%	100%		14.630					**LM**
13	35	14.63		23.80	33.10	19.019	3.400%	0.497	30%	4.39	6.58	10%	90%	1.463	13.167					**FA1**
14				23.80	32.91	19.019	3.400%	0.497	30%	4.39	6.58	20%	80%	2.926	11.704					**FA1**
15				23.80	32.73	19.019	3.400%	0.497	30%	4.39	6.58	30%	70%	4.389	10.241					**FA1**
16				23.80	32.54	19.019	3.400%	0.497	30%	4.39	6.58	40%	60%	5.852	8.778					**FA1**
17	35	14.63		23.80	33.10	19.019	3.400%	0.497	30%	4.39	6.58	10%	90%	1.463	13.167					**FA2**
18				23.80	32.91	19.019	3.400%	0.497	30%	4.39	6.58	20%	80%	2.926	11.704					**FA2**
19				23.80	32.73	19.019	3.400%	0.497	30%	4.39	6.58	30%	70%	4.389	10.241					**FA2**
20				23.80	32.54	19.019	3.400%	0.497	30%	4.39	6.58	40%	60%	5.852	8.778					**FA2**
21	35	14.63		23.80	32.99	19.019	3.400%	0.497	30%	4.39	6.58					30%	70%	4.389	10.241	**Slag**
22				23.80	32.89	19.019	3.400%	0.497	30%	4.39	6.58					40%	60%	5.852	8.778	**Slag**
23				23.80	32.79	19.019	3.400%	0.497	30%	4.39	6.58					50%	50%	7.315	7.315	**Slag**
24				23.80	32.69	19.019	3.400%	0.497	30%	4.39	6.58					60%	40%	8.778	5.852	**Slag**
25				23.80	32.59	19.019	3.400%	0.497	30%	4.39	6.58					70%	30%	10.241	4.389	**Slag**

Table E.2: Test results for C1 using SP2

Mix	Slump Flow				V-funnel	L-Box									segregation Ratio			
	X (mm)	Y (mm)	Ave	T500 (sec)	Tf (sec)	H1.1	H1.2	H1.3	H1	H2.1	H2.2	H2.3	H2	passing ratio	Pan	Mass of Con	Lift sieve and record mass	SR
1	450	500	475	2.2	5.10	500	500	500	500	60	60	60	60	0.90	1.38	4.9	1.5	2.4%
2	510	600	555	2.0	4.00	500	500	500	500	60	60	60	60	0.90	1.38	4.8	1.4	0.4%
3	610	630	620	1.50	3.62	500	500	500	500	60	60	60	60	0.90	1.38	4.98	2.06	13.7%
4	660	670	665	1.20	3.32	500	500	500	500	60	60	60	60	0.90	1.38	5.22	2.3	17.6%
5	680	690	685	1.40	3.50	500	500	500	500	60	60	60	60	0.90	1.38	4.98	2.2	16.5%
6	720	740	730	1.00	3.40	500	500	500	500	60	60	60	60	0.90	1.38	4.88	2.69	26.8%
7	760	760	760	1.12	3.75	500	500	500	500	60	60	60	60	0.90	1.38	5.00	2.36	19.6%
8	790	800	795	1.10	3.50	500	500	500	500	60	60	60	60	0.90	1.38	8.9	3.1	19.3%
9	760	760	760	1.12	3.75	500	500	500	500	60	60	60	60	0.90	1.38	5	2.36	19.6%
10	730	720	725	1.10	3.6	500	500	500	500	60	60	60	60	0.90	1.38	4.88	2	12.7%
11	680	650	665	2.00	3.7	500	500	500	500	60	60	60	60	0.90	1.38	4.8	1.8	8.8%
12	640	635	637.5	2.20	3.5	500	500	500	500	60	60	60	60	0.90	1.38	4.9	1.9	10.6%
13	770	760	765	1.19	3.6	500	500	500	500	60	60	60	60	0.90	1.38	4.880	2.360	20.1%
14	750	710	730	1.16	4.7	500	500	500	500	60	60	60	60	0.90	1.38	5.200	2.840	28.1%
15	800	810	805	1.34	4.7	500	500	500	500	60	60	60	60	0.90	1.38	4.920	3.320	39.4%
16	790	820	805	1.31	5.3	500	500	500	500	60	60	60	60	0.90	1.38	4.880	4.080	55.3%
			0															
17	815	825	820	0.8	3.80	500	505	510	505	55	60	60	58	0.96	1.38	4.940	4.220	57.5%
18	830	830	830	0.7	3.85	510	510	515	512	55	55	55	55	1.08	1.38	5.000	4.580	64.0%
19	850	870	860	0.5	4.44	510	510	510	510	55	55	55	55	1.06	1.38	4.820	5.060	76.3%
20	900	900	900	0.5	16.80	515	515	510	513	55	55	55	55	1.10	1.38	5.000	5.340	79.2%
			0															
21	880	870	875	1.03	5.4	500	500	500	500	60	60	60	60	0.90	1.38	4.920	4.480	63.0%
22	895	880	887.5	0.72	4.4	500	500	500	500	60	60	60	60	0.90	1.38	4.900	3.860	50.6%
23	880	900	890	0.8	6.1	500	500	500	500	60	60	60	60	0.90	1.38	5.000	4.800	68.4%
24	900	900	900	0.8	5.2	500	500	500	500	60	60	60	60	0.90	1.38	5.200	5.100	71.5%
25	900	900	900	1	12.8	500	500	500	500	60	60	60	60	0.90	1.38	5.100	4.920	69.4%

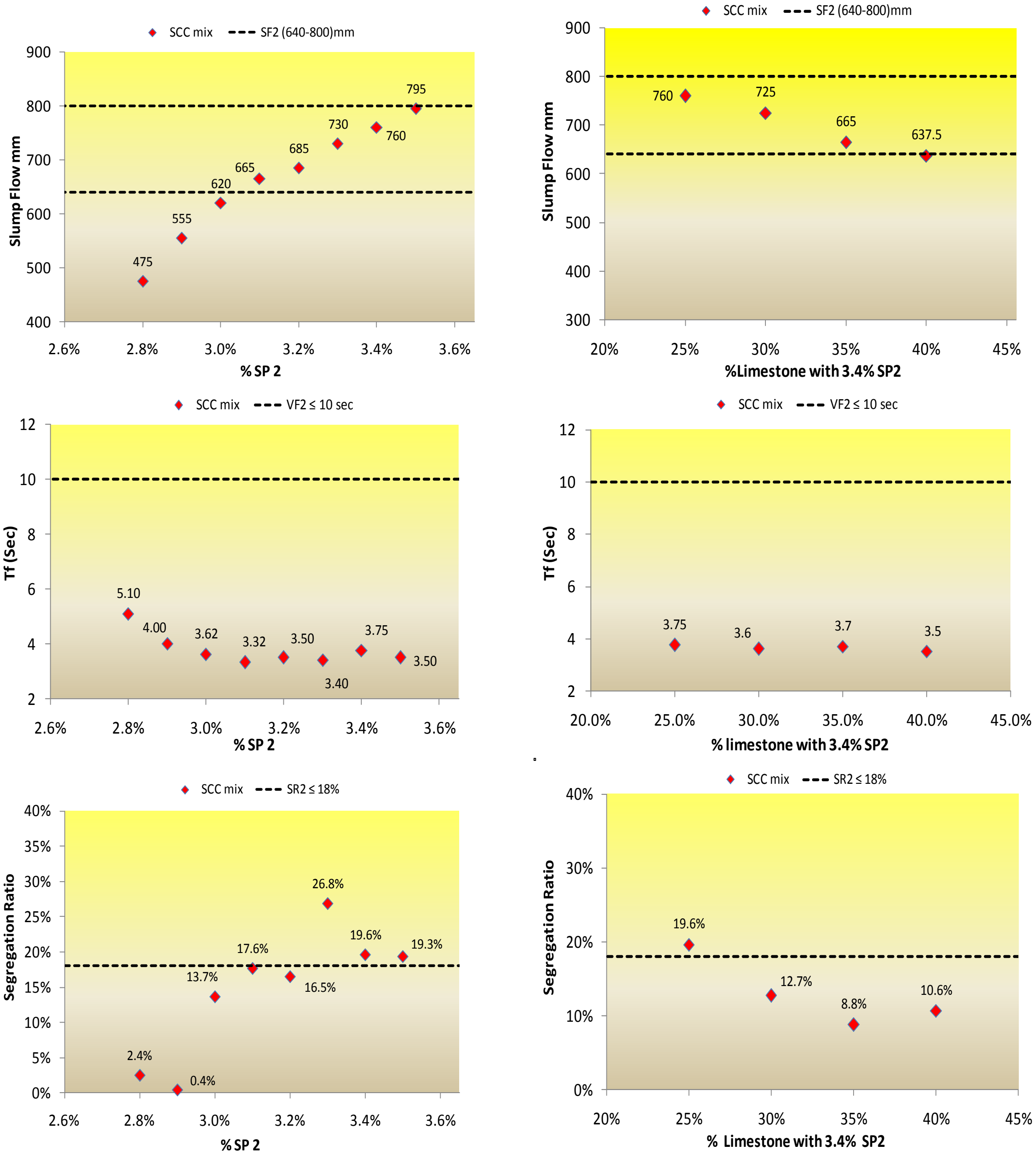

Figure E.1: SCC property results relative to SP and limestone percentage using SP2 optimum dosage on C1

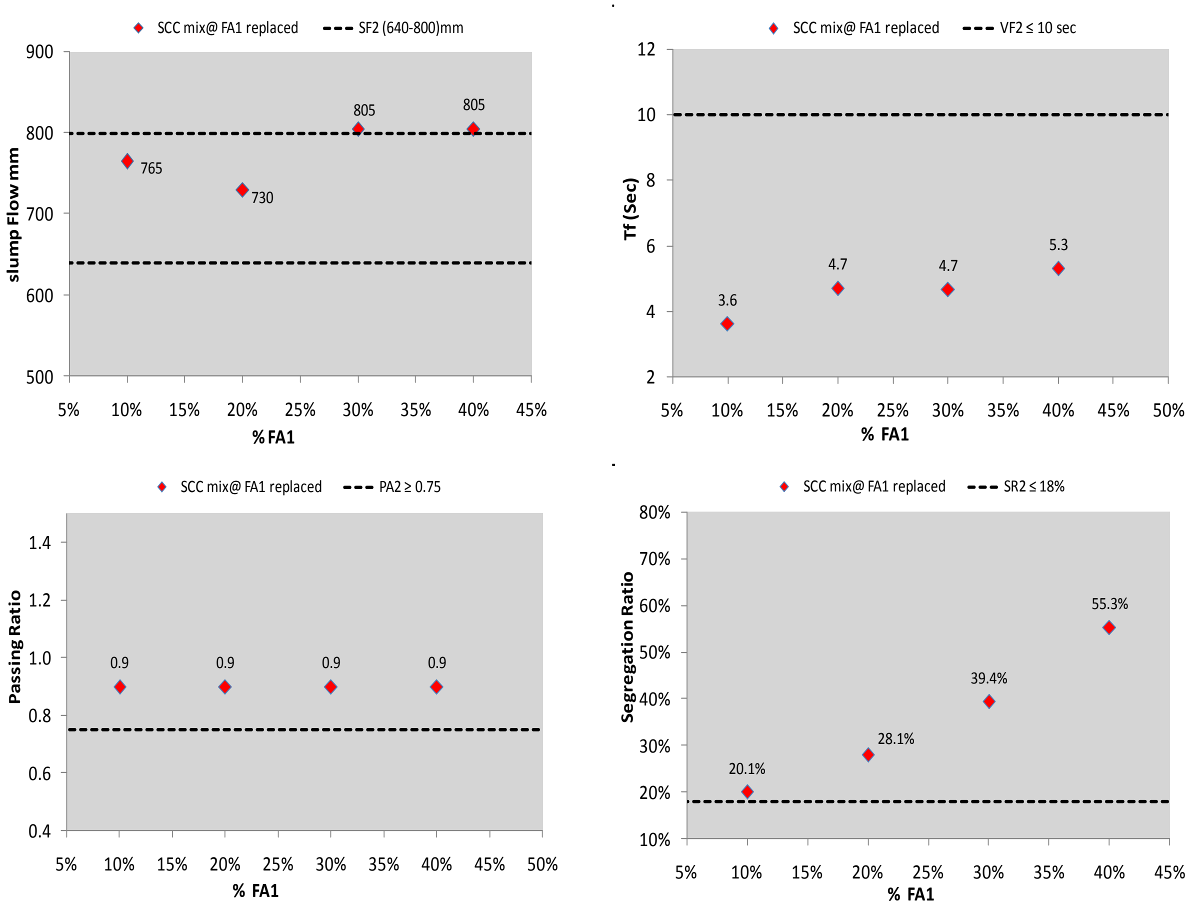

Figure E.2: Effect of replacing C1 with FA1 on SCC properties at sufficient SP2 concentration

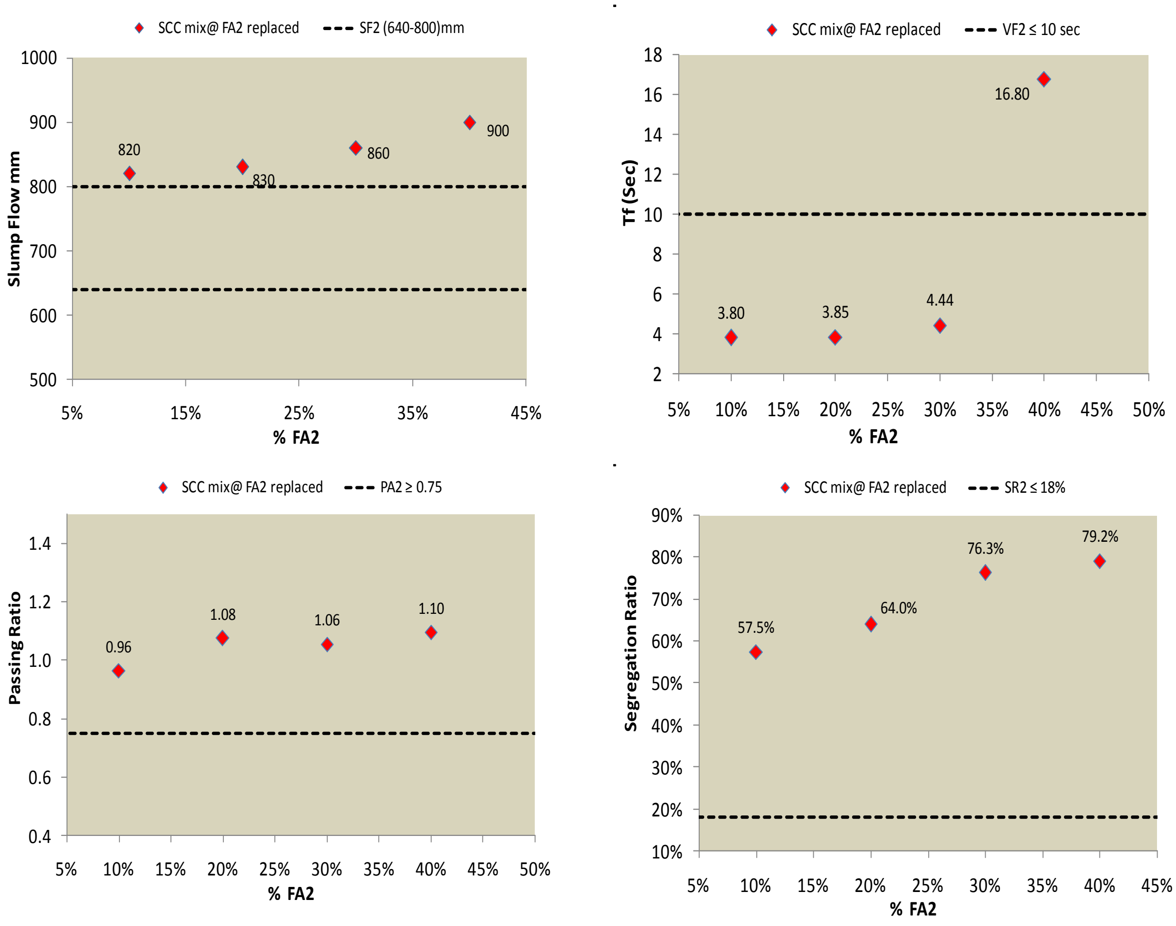

Figure E.3: Effect of replacing C1 with FA2 on SCC properties at sufficient SP2 concentration

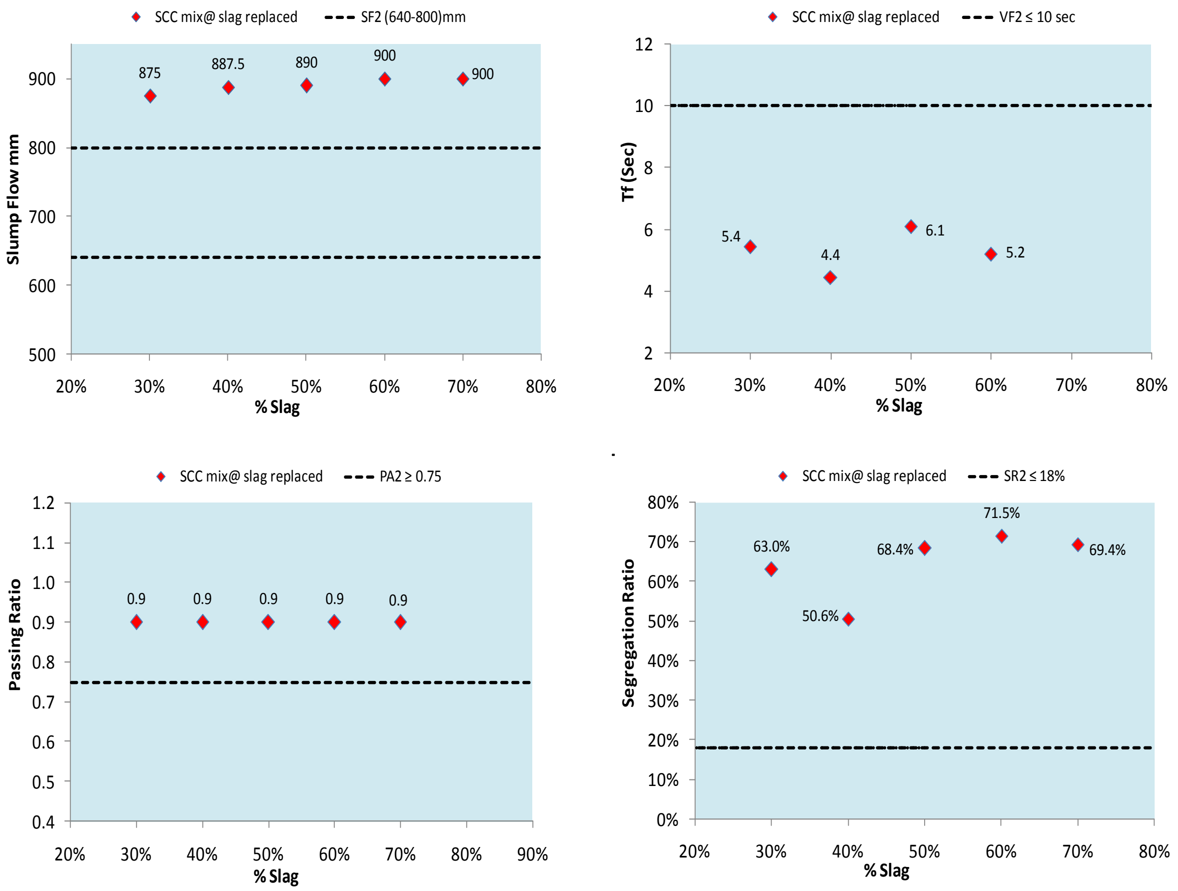

Figure E.4: Effect of replacing C1 with slag on SCC properties at sufficient SP2 concentration

Appendix F. (C2 with SP2)

Table F.1: Mix proportions for C2 using SP2

Mix	Date	Litre	Cementations kg	w/c	Stone kg	Sand kg	Fines kg	SP %	SP kg	CD %	CD kg	Water kg	FA / C %		Fly Ash kg	Cement kg	S / C %		Slag kg	Cement kg	Variables
100		35	14.63		23.80	39.06	18.288	2.600%	0.380	25%	3.66	4.70		100%		14.630					**SP2**
101					17.00	45.38	18.288	2.700%	0.395	25%	3.66	4.70		100%		14.630					**SP2**
102					17.00	45.34	18.288	2.800%	0.410	25%	3.66	4.70		100%		14.630					**SP2**
103					17.00	45.31	18.288	2.900%	0.424	25%	3.66	4.70		100%		14.630					**SP2**
104					17.00	45.27	18.288	3.000%	0.439	25%	3.66	4.70		100%		14.630					**SP2**
105					17.00	45.24	18.288	3.100%	0.454	25%	3.66	4.70		100%		14.630					**SP2**
106					17.00	45.21	18.288	3.200%	0.468	25%	3.66	4.70		100%		14.630					**SP2**
107					17.00	45.17	18.288	3.300%	0.483	25%	3.66	4.70		100%		14.630					**SP2**
108		35	14.63		17.00	44.76	18.288	2.900%	0.424	25%	3.66	4.70	30%	70%	4.389	10.241					**LM**
109					17.00	43.88	19.019	2.900%	0.424	30%	4.39	4.70	40%	60%	5.852	8.778					**LM**
110					17.00	43.01	19.751	2.900%	0.424	35%	5.12	4.70	50%	50%	7.315	7.315					**LM**
111					17.00	42.14	20.482	2.900%	0.424	40%	5.85	4.70	60%	40%	8.778	5.852					**LM**
112		35	14.63		23.80	33.96	18.288	2.900%	0.424	25%	3.66	6.58	10%	90%	1.463	13.167					**FA1**
113					23.80	33.77	18.288	2.900%	0.424	25%	3.66	6.58	20%	80%	2.926	11.704					**FA1**
114					23.80	33.59	18.288	2.900%	0.424	25%	3.66	6.58	30%	70%	4.389	10.241					**FA1**
115					23.80	33.41	18.288	2.900%	0.424	25%	3.66	6.58	40%	60%	5.852	8.778					**FA1**
116		35	14.63		23.80	33.96	18.288	2.900%	0.424	25%	3.66	6.58	10%	90%	1.463	13.167					**FA2**
117					23.80	33.77	18.288	2.900%	0.424	25%	3.66	6.58	20%	80%	2.926	11.704					**FA2**
118					23.80	33.59	18.288	2.900%	0.424	25%	3.66	6.58	30%	70%	4.389	10.241					**FA2**
119					23.80	33.41	18.288	2.900%	0.424	25%	3.66	6.58	40%	60%	5.852	8.778					**FA2**
120		35	14.63		23.80	33.85	18.288	2.900%	0.424	25%	3.66	6.58					30%	70%	4.389	10.241	**Slag**
121					23.80	33.75	18.288	2.900%	0.424	25%	3.66	6.58					40%	60%	5.852	8.778	**Slag**
122					23.80	33.65	18.288	2.900%	0.424	25%	3.66	6.58					50%	50%	7.315	7.315	**Slag**
123					23.80	33.55	18.288	2.900%	0.424	25%	3.66	6.58					60%	40%	8.778	5.852	**Slag**
124					23.80	33.45	18.288	2.900%	0.424	25%	3.66	6.58					70%	30%	10.241	4.389	**Slag**

Table F.2: Test results for C2 using SP2

	Slump Flow				V-funnel	L-Box							Segregation ratio			
Mix	X (mm)	Y (mm)	Ave	T500 (sec)	Tf (sec)	H1.1	H1.2	H1	H2.1	H2.2	H2	passing ratio	Mass Sieve	Mass of Con	Lift sieve and record mass	SR
100	680	660	670	1.0	5.20	490	500	495	55	55	55	0.90	1.38	4.88	1.41	0.6%
101	710	710	710	1.2	4.88	490	500	495	55	55	55	0.90	1.38	5.04	1.48	2.0%
102	710	720	715	1.22	4.34	490	500	495	55	55	55	0.90	1.38	4.85	1.68	6.2%
103	730	730	730	1.16	4.93	490	500	495	55	55	55	0.90	1.38	4.86	1.63	5.1%
104	740	750	745	1.06	4.01	490	500	495	55	55	55	0.90	1.38	4.85	1.44	1.2%
105	765	760	762.5	1.30	5.80	490	500	495	55	55	55	0.90	1.38	4.98	1.6	4.4%
106	770	800	785	1.40	6.10	490	500	495	55	55	55	0.90	1.38	5.1	1.8	8.2%
107	800	810	805	1.55	6.90	490	500	495	55	55	55	0.90	1.38	5.2	2.42	20.0%
108	730	730	730	1.16	4.93	490	500	495	55	55	55	0.90	1.38	4.86	1.63	5.1%
109	710	700	705	1.26	4.2	490	500	495	55	55	55	0.90	1.38	4.82	1.8	8.7%
110	640	630	635	1.21	4.8	490	500	495	55	55	55	0.90	1.38	5	1.5	2.4%
111	630	650	640	1.30	3.8	490	500	495	55	55	55	0.90	1.38	4.94	1.48	2.0%
112	780	800	790	0.96	5.2	490	500	495	55	55	55	0.90	1.380	4.960	2.800	28.6%
113	800	785	792.5	1.09	5.1	490	495	492.5	60	60	60	0.84	1.380	4.940	2.900	30.8%
114	860	815	837.5	1.12	5.3	500	500	500	60	60	60	0.90	1.380	5.080	2.980	31.5%
115	795	810	802.5	1.20	6.1	500	500	500	60	60	60	0.90	1.380	4.960	3.400	40.7%
116	840	820	830	0.97	3.87	495	496	495.5	59	57	58	0.88	1.380	4.900	2.940	31.8%
117	820	800	810	0.82	3.56	495	498	496.5	60	58	59	0.88	1.380	5.260	3.620	42.6%
118	880	860	870	0.78	3.41	500	500	500	60	60	60	0.90	1.380	4.920	3.820	49.6%
119	900	900	900	0.6	2.75	500	500	500	60	60	60	0.90	1.380	4.880	2.540	23.8%
120	820	830	825	1.09	5.3	495	499	497	58	60	59	0.88	1.380	4.860	3.700	47.7%
121	835	815	825	1.06	5.1	500	500	500	60	60	60	0.90	1.380	4.920	3.120	35.4%
122	870	880	875	0.7	4.6	500	500	500	60	60	60	0.90	1.380	4.880	3.820	50.0%
123	860	870	865	1.22	6.1	500	500	500	60	60	60	0.90	1.380	5.060	4.500	61.7%
124	880	870	875	0.9	5.5	500	500	500	60	60	60	0.90	1.380	5.200	3.200	35.0%

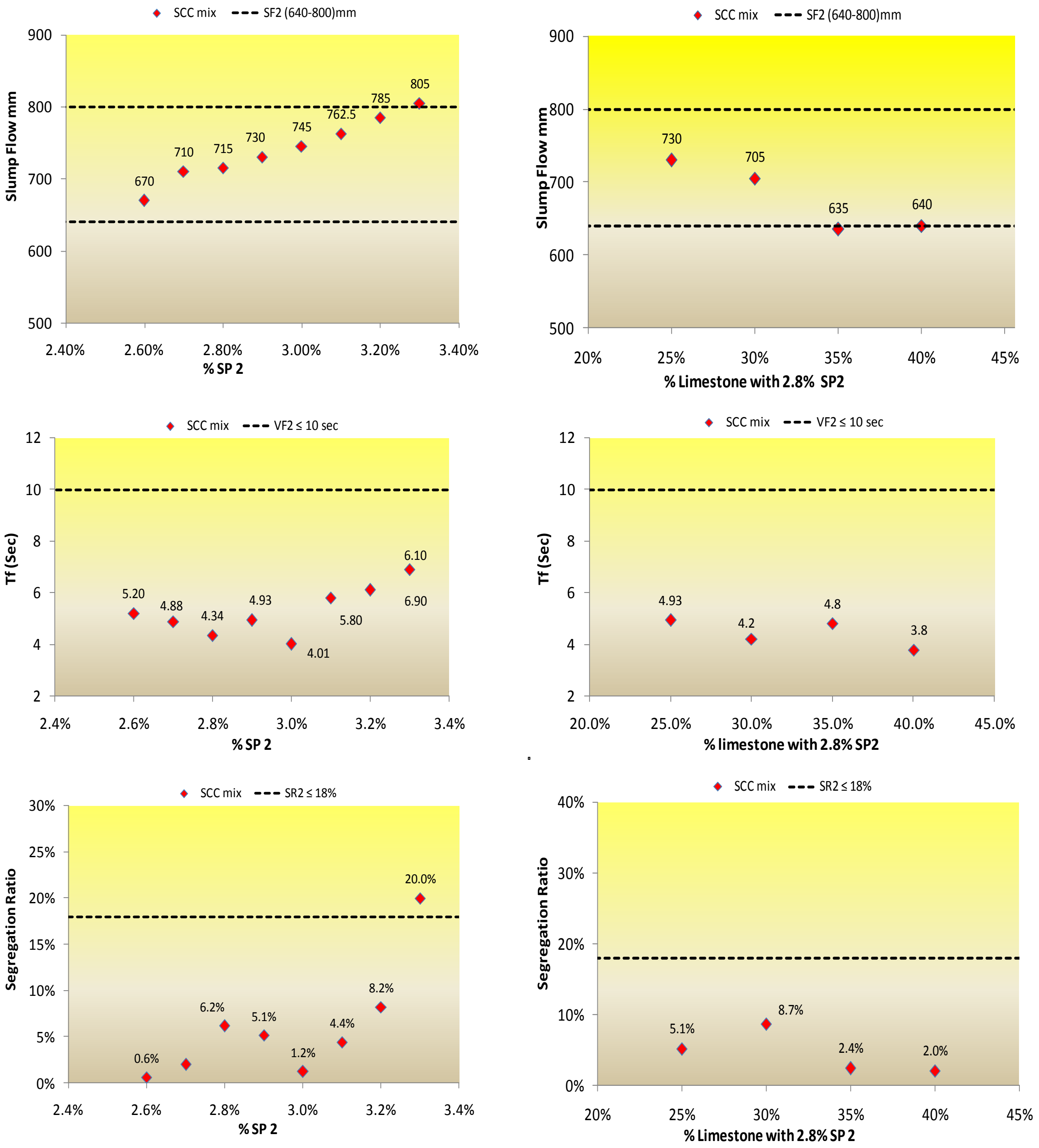

Figure F.1: SCC property results relative to SP and limestone percentage using SP2 optimum dosage on C2

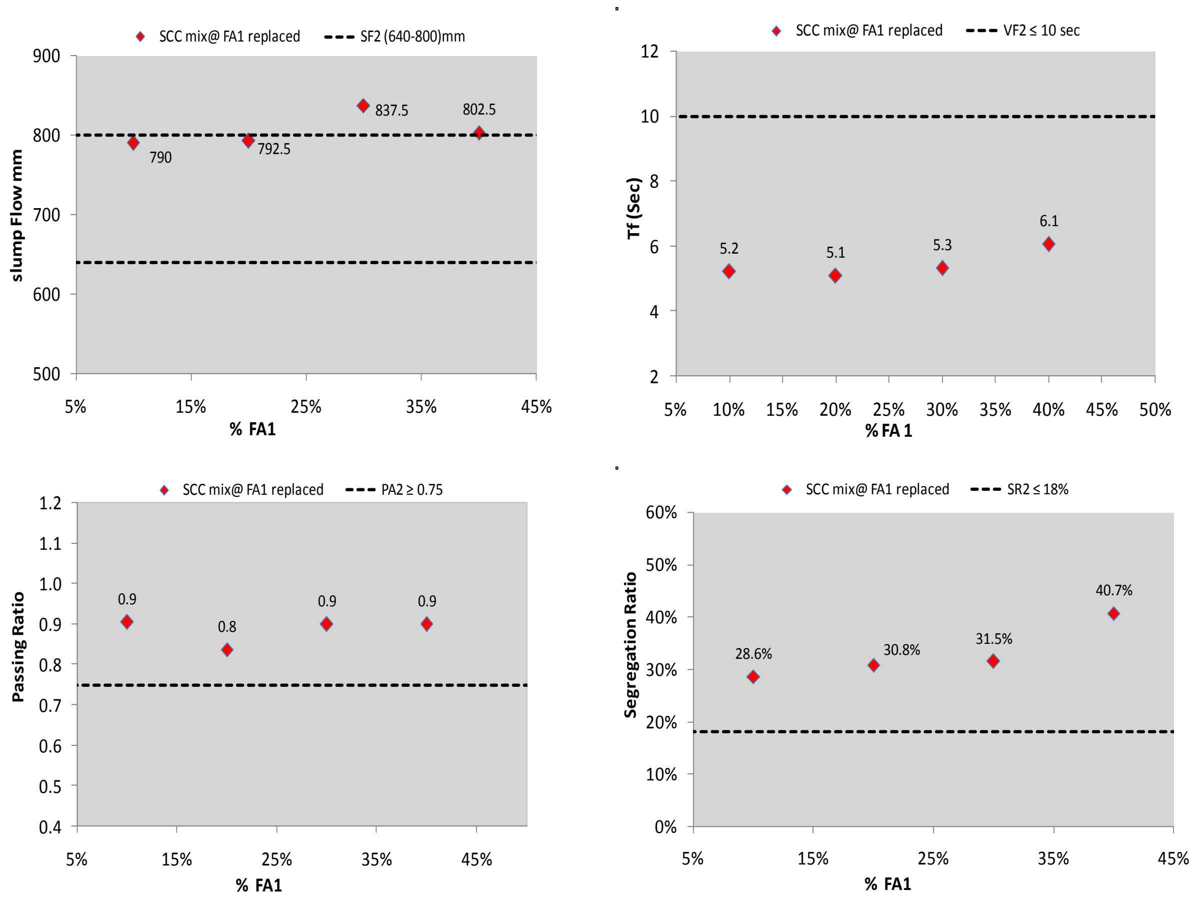

Figure F.2: Effect of replacing C2 with FA1 on SCC properties at sufficient SP2 concentration

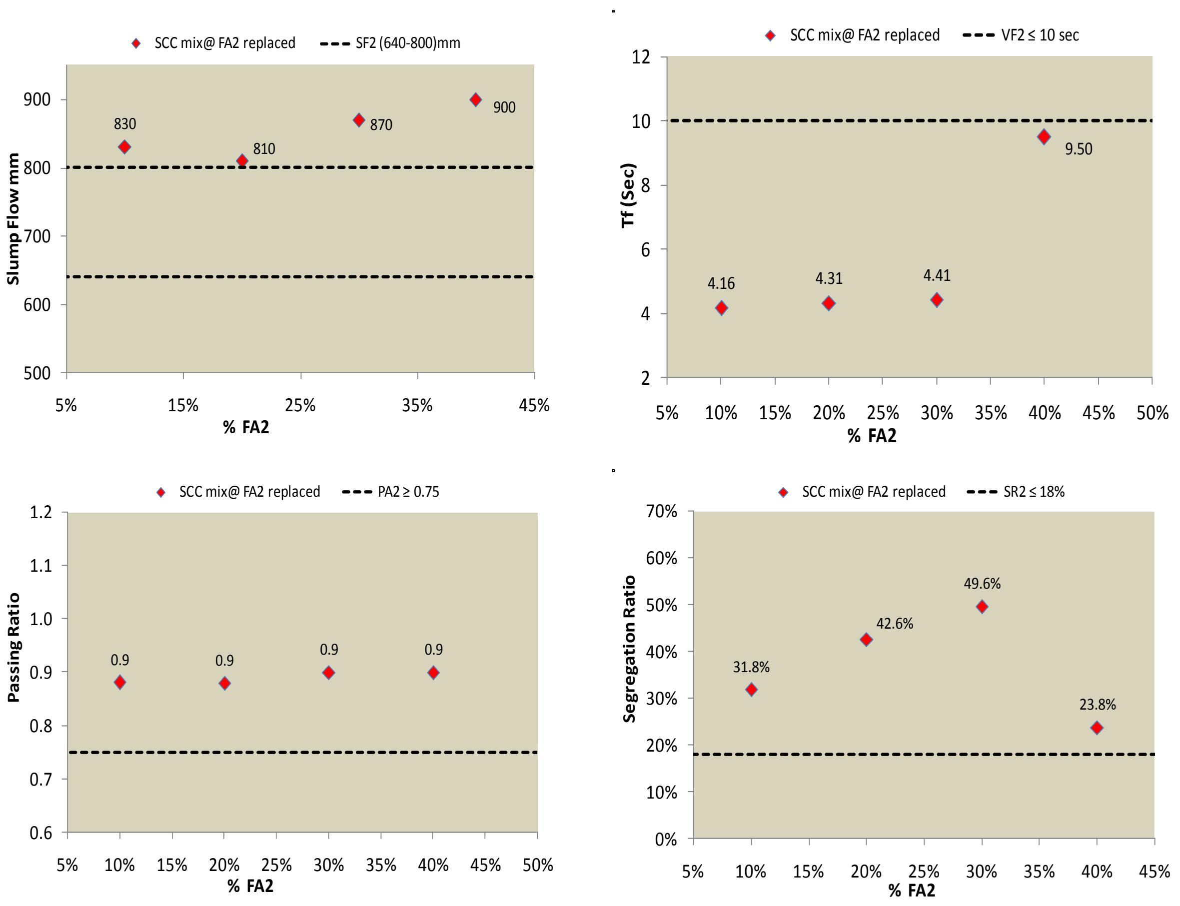

Figure F.3: Effect of replacing C2 with FA2 on SCC properties at sufficient SP2 concentration

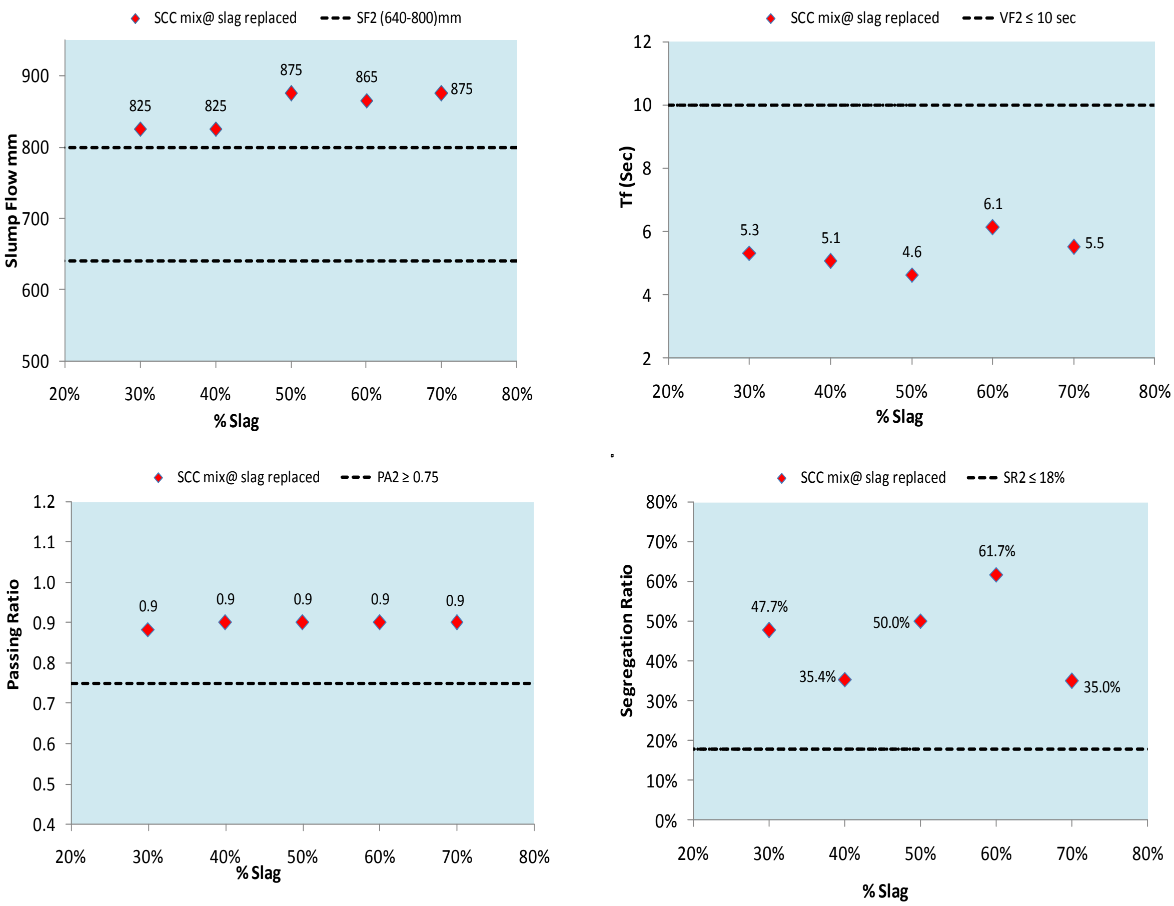

Figure F.4 Effect of replacing C2 with slag on SCC properties at sufficient SP2 concentration

Appendix G. (C3 with SP2)

- Table G.1: Mix proportions for C3 using SP2
- Table G.2: Test results for C3 using SP2
- Figure J.1: SCC property results relative to SP and limestone percentage using SP2 sufficient dosage on C3
- Figure G.2: Effect of replacing C3 with FA1 on SCC properties at sufficient SP2 concentration
- Figure G.3: Effect of replacing C3 with FA2 on SCC properties at sufficient SP2 concentration
- Figure G.4: Effect of replacing C3 with slag on SCC properties at sufficient SP2 concentration

Table G.1: Mix proportions for C3 using SP2

Mix	Litre	Cementations kg	w/c	Stone kg	Sand kg	Fines kg	SP %	SP kg	CD %	CD kg	Water kg	FA / C %		Fly Ash kg	Cement kg	S / C %		Slag kg	Cement kg	
65	35	14.63		17.00	45.38	18.288	2.700%	0.395	25%	3.66	4.70		100%		14.630					**SP2**
66				17.00	45.34	18.288	2.800%	0.410	25%	3.66	4.70		100%		14.630					**SP2**
67				17.00	45.31	18.288	2.900%	0.424	25%	3.66	4.70		100%		14.630					**SP2**
68				17.00	45.27	18.288	3.000%	0.439	25%	3.66	4.70		100%		14.630					**SP2**
69				17.00	45.24	18.288	3.100%	0.454	25%	3.66	4.70		100%		14.630					**SP2**
70				17.00	45.21	18.288	3.200%	0.468	25%	3.66	4.70		100%		14.630					**SP2**
71				17.00	45.17	18.288	3.300%	0.483	25%	3.66	4.70		100%		14.630					**SP2**
72				17.00	45.14	18.288	3.400%	0.497	25%	3.66	4.70		100%		14.630					**SP2**
73				17.00	89.60	14.108	3.500%	0.512	25%	3.66	4.70		100%		10.450					**SP2**
74				17.00	89.60	14.108	3.600%	0.527	25%	3.66	4.70		100%		10.450					**SP2**
75	35	14.63		17.00	44.62	18.288	3.300%	0.483	25%	3.66	4.70	30%	70%	4.389	10.241					**LM**
76				17.00	43.75	19.019	3.300%	0.483	30%	4.39	4.70	40%	60%	5.852	8.778					**LM**
77				17.00	42.87	19.751	3.300%	0.483	35%	5.12	4.70	50%	50%	7.315	7.315					**LM**
78				17.00	42.00	20.482	3.300%	0.483	40%	5.85	4.70	60%	40%	8.778	5.852					**LM**
79	35	14.63		23.80	33.82	18.288	3.300%	0.483	25%	3.66	6.58	10%	90%	1.463	13.167					**FA1**
80				23.80	33.64	18.288	3.300%	0.483	25%	3.66	6.58	20%	80%	2.926	11.704					**FA1**
81				23.80	33.45	18.288	3.300%	0.483	25%	3.66	6.58	30%	70%	4.389	10.241					**FA1**
82				23.80	33.27	18.288	3.300%	0.483	25%	3.66	6.58	40%	60%	5.852	8.778					**FA1**
83	35	14.63		23.80	33.82	18.288	3.300%	0.483	25%	3.66	6.58	10%	90%	1.463	13.167					**FA2**
84				23.80	33.64	18.288	3.300%	0.483	25%	3.66	6.58	20%	80%	2.926	11.704					**FA2**
85				23.80	33.45	18.288	3.300%	0.483	25%	3.66	6.58	30%	70%	4.389	10.241					**FA2**
86				23.80	33.27	18.288	3.300%	0.483	25%	3.66	6.58	40%	60%	5.852	8.778					**FA2**
87	35	14.63		23.80	33.71	18.288	3.300%	0.483	25%	3.66	6.58					30%	70%	4.389	10.241	**Slag**
88				23.80	33.61	18.288	3.300%	0.483	25%	3.66	6.58					40%	60%	5.852	8.778	**Slag**
89				23.80	33.51	18.288	3.300%	0.483	25%	3.66	6.58					50%	50%	7.315	7.315	**Slag**
90				23.80	33.41	18.288	3.300%	0.483	25%	3.66	6.58					60%	40%	8.778	5.852	**Slag**
91				23.80	33.31	18.288	3.300%	0.483	25%	3.66	6.58					70%	30%	10.241	4.389	**Slag**

Table G.2: Test results for C3 using SP2

	Slump Flow				V-funnel	L-Box							Segregation ratio			
Mix	X (mm)	Y (mm)	Ave	T500 (sec)	Tf (sec)	H1.1	H1.2	H1	H2.1	H2.2	H2	passing ratio	Mass Sieve	Mass of Con	Lift sieve and record mass	SR
65	640	640	640	0.5	3.35	500	500	500	60	60	60	0.90	1.38	4.96	1.45	1.4%
66	640	630	635	0.4	4.12	500	500	500	60	60	60	0.90	1.38	4.82	1.76	7.9%
67	660	685	672.5	0.50	4.44	500	500	500	60	60	60	0.90	1.38	4.88	1.8	8.6%
68	685	690	687.5	0.53	4.25	500	500	500	60	60	60	0.90	1.38	4.84	1.92	11.2%
69	680	700	690	0.97	4.19	500	500	500	60	60	60	0.90	1.38	4.88	2.3	18.9%
70	700	710	705	1.13	3.88	500	500	500	60	60	60	0.90	1.38	5.16	2.2	15.9%
71	720	730	725	1.00	3.75	500	500	500	60	60	60	0.90	1.38	5.02	1.96	11.6%
72	750	740	745	1.00	4.34	500	500	500	60	60	60	0.90	1.38	4.94	2.24	17.4%
73	760	760	760	1.30	5.30	500	500	500	60	60	60	0.90	1.38	5.2	2.6	23.5%
74	780	790	785	1.80	6.40	500	500	500	60	60	60	0.90	1.38	4.88	2.2	16.8%
75	720	730	725	1.00	3.75	500	500	500	60	60	60	0.90	1.38	5.02	1.96	11.6%
76	700	685	692.5	1.90	5.1	500	500	500	60	60	60	0.90	1.38	4.92	2.28	18.3%
77	690	665	677.5	1.44	5.2	500	500	500	60	60	60	0.90	1.38	4.92	2.14	15.4%
78	640	665	652.5	1.57	5.2	500	500	500	60	60	60	0.90	1.38	5	2.04	13.2%
79	760	670	715	1.16	5.4	500	500	500	55	55	55	0.95	1.380	5.080	2.800	28.0%
80	800	800	800	0.91	4.7	500	500	500	60	60	60	0.90	1.380	4.860	3.180	37.0%
81	795	780	787.5	1.31	5.1	500	500	500	60	60	60	0.90	1.380	5.260	3.200	34.6%
82	790	775	782.5	1.21	5.1	500	500	500	60	60	60	0.90	1.380	4.940	3.300	38.9%
83	845	800	822.5	0.7	3.75	500	500	500	59	57	58	0.92	1.380	4.940	2.540	23.5%
84	850	820	835	3.97	4.31	495	500	497.5	60	58	59	0.89	1.380	4.960	3.340	39.5%
85	780	810	795	0.69	2.87	500	500	500	60	60	60	0.90	1.380	5.340	4.200	52.8%
86	820	850	835	0.6	4.50	496	500	498	60	60	60	0.88	1.380	4.800	2.820	30.0%
87	830	795	812.5	1.22	5.2	500	500	500	58	60	59	0.91	1.380	5.020	2.520	22.7%
88	855	860	857.5	0.97	4.3	500	498	499	55	60	57.5	0.92	1.380	5.220	4.320	56.3%
89	850	850	850	0.84	5.1	500	495	497.5	60	57	58.5	0.89	1.380	5.100	4.240	56.1%
90	850	850	850	0.75	8.6	500	500	500	60	60	60	0.90	1.380	5.180	4.980	69.5%
91	850	850	850	0.8	7.9	500	500	500	60	60	60	0.90	1.380	4.880	4.800	70.1%

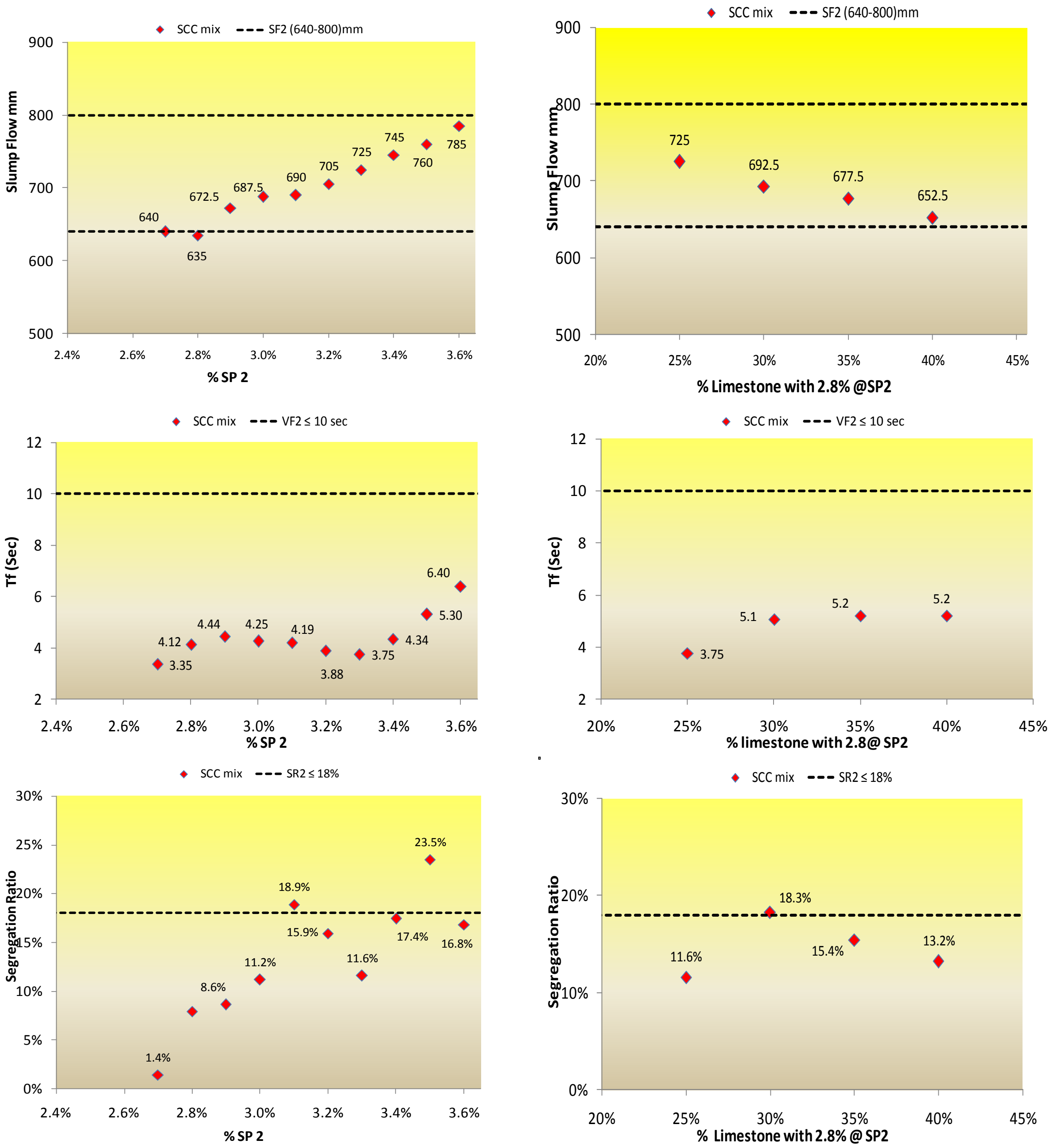

Figure G.1: SCC property results relative to SP and limestone percentage using SP2 optimum dosage on C3

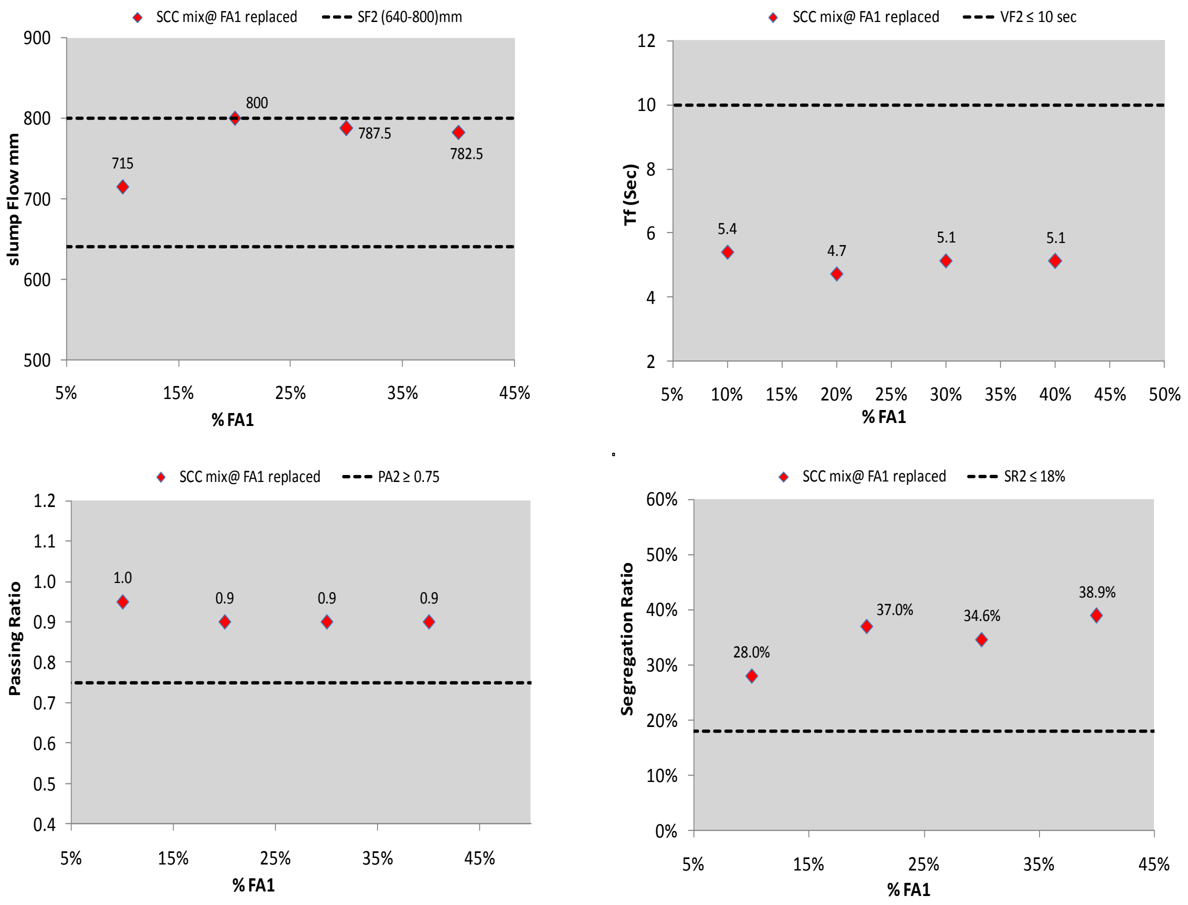

Figure G.2: Effect of replacing C3 with FA1 on SCC properties at sufficient SP2 concentration

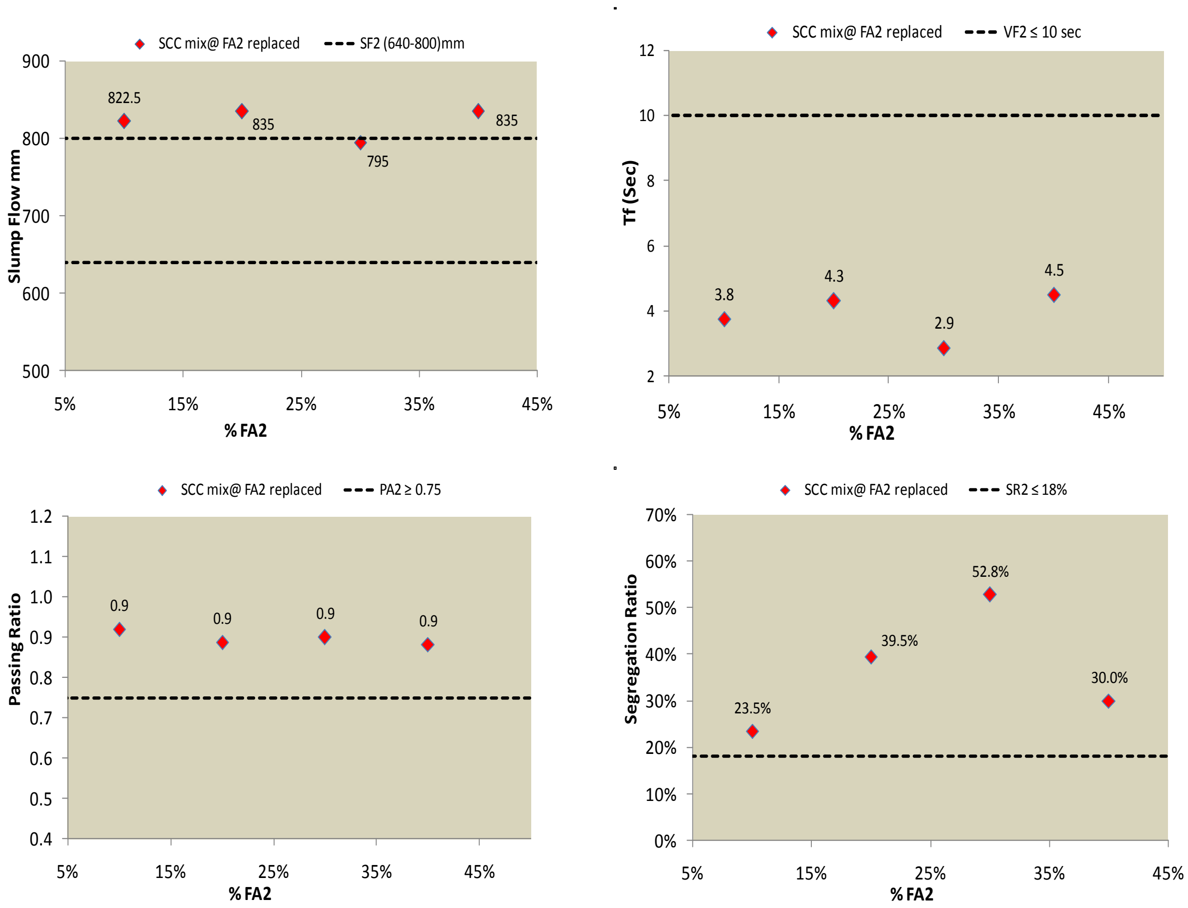

Figure G.3: Effect of replacing C3 with FA2 on SCC properties at sufficient SP2 concentration

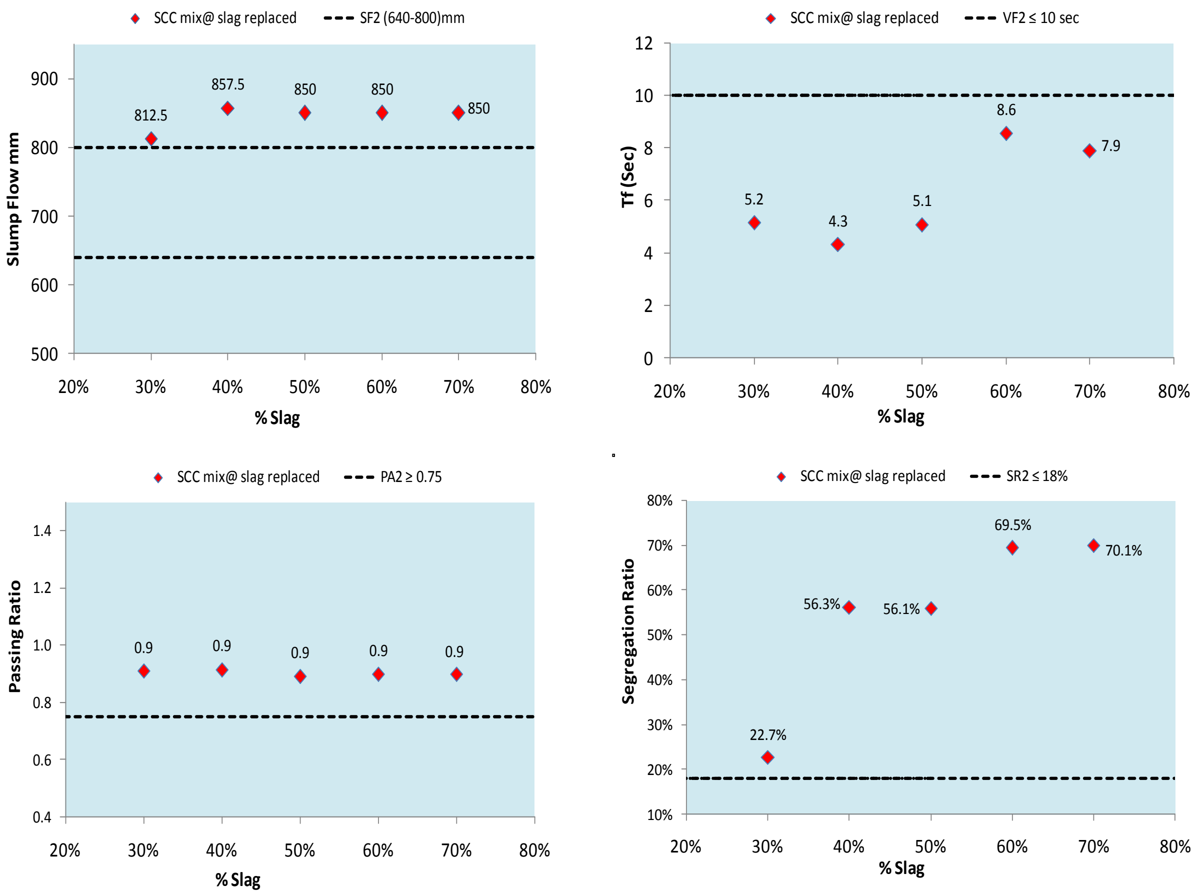

Figure G.4: Effect of replacing C3 with slag on SCC properties at sufficient SP2 concentration

Appendix H. (C4 with SP2)

Table H.1: Mix proportions for C4 using SP2

Mix	Litre	Cementations kg	w/c	Stone kg	Sand kg	Fines kg	SP %	SP kg	CD %	CD kg	Water kg	FA / C %		Fly Ash kg	Cement kg	S / C %		Slag kg	Cement kg	Variables
100	35	14.63		17.00	45.45	18.288	2.5%	0.366	25%	3.66	4.70		100%		14.630					**SP2**
101				17.00	45.41	18.288	2.6%	0.380	25%	3.66	4.70		100%		14.630					**SP2**
102				17.00	45.38	18.288	2.7%	0.395	25%	3.66	4.70		100%		14.630					**SP2**
103				17.00	45.34	18.288	2.8%	0.410	25%	3.66	4.70		100%		14.630					**SP2**
104				17.00	45.31	18.288	2.9%	0.424	25%	3.66	4.70		100%		14.630					**SP2**
105				17.00	45.27	18.288	3.0%	0.439	25%	3.66	4.70		100%		14.630					**SP2**
106				17.00	45.24	18.288	3.1%	0.454	25%	3.66	4.70		100%		14.630					**SP2**
107				17.00	45.21	18.288	3.2%	0.468	25%	3.66	4.70		100%		14.630					**SP2**
108	35	14.63		17.00	44.79	18.288	2.8%	0.410	25%	3.66	4.70	30%	70%	4.389	10.241					**LM**
109				17.00	43.92	19.019	2.8%	0.410	30%	4.39	4.70	40%	60%	5.852	8.778					**LM**
110				17.00	43.05	19.751	2.8%	0.410	35%	5.12	4.70	50%	50%	7.315	7.315					**LM**
111				17.00	42.17	20.482	2.8%	0.410	40%	5.85	4.70	60%	40%	8.778	5.852					**LM**
112	35	14.63		23.80	33.31	19.019	2.8%	0.410	30%	4.39	6.58	10%	90%	1.463	13.167					**FA1**
113				23.80	33.12	19.019	2.8%	0.410	30%	4.39	6.58	20%	80%	2.926	11.704					**FA1**
114				23.80	32.94	19.019	2.8%	0.410	30%	4.39	6.58	30%	70%	4.389	10.241					**FA1**
115				23.80	32.75	19.019	2.8%	0.410	30%	4.39	6.58	40%	60%	5.852	8.778					**FA1**
116	35	14.63		23.80	33.31	19.019	2.8%	0.410	30%	4.39	6.58	10%	90%	1.463	13.167					**FA2**
117				23.80	33.12	19.019	2.8%	0.410	30%	4.39	6.58	20%	80%	2.926	11.704					**FA2**
118				23.80	32.94	19.019	2.8%	0.410	30%	4.39	6.58	30%	70%	4.389	10.241					**FA2**
119				23.80	32.75	19.019	2.8%	0.410	30%	4.39	6.58	40%	60%	5.852	8.778					**FA2**
120	35	14.63		23.80	33.19	19.019	2.8%	0.410	30%	4.39	6.58					30%	70%	4.389	10.241	**Slag**
121				23.80	33.09	19.019	2.8%	0.410	30%	4.39	6.58					40%	60%	5.852	8.778	**Slag**
122				23.80	33.00	19.019	2.8%	0.410	30%	4.39	6.58					50%	50%	7.315	7.315	**Slag**
123				23.80	32.90	19.019	2.8%	0.410	30%	4.39	6.58					60%	40%	8.778	5.852	**Slag**
124				23.80	32.80	19.019	2.8%	0.410	30%	4.39	6.58					70%	30%	10.241	4.389	**Slag**

Table H.2: Test results for C4 using SP2

Mix	Slump Flow				V-funnel	L-Box							Segregation ratio			
	X (mm)	Y (mm)	Ave	T500 (sec)	Tf (sec)	H1.1	H1.2	H1	H2.1	H2.2	H2	passing ratio	Mass Sieve	Mass of Con	Lift sieve and record mass	SR
100	650	640	645	1.9	5.20	490	500	495	55	55	55	0.90	1.38	4.82	1.38	0.0%
101	665	630	647.5	1.1	4.31	490	500	495	55	55	55	0.90	1.38	4.96	1.7	6.5%
102	655	685	670	1.12	4.44	490	500	495	55	55	55	0.90	1.38	4.84	2.28	18.6%
103	690	710	700	0.90	3.87	490	500	495	55	55	55	0.90	1.38	4.88	2.23	17.4%
104	730	740	735	1.00	4.06	490	500	495	55	55	55	0.90	1.38	4.94	2.35	19.6%
105	750	780	765	1.20	4.80	490	500	495	55	55	55	0.90	1.38	4.82	2.38	20.7%
106	770	800	785	2.50	6.00	490	500	495	55	55	55	0.90	1.38	4.9	2.45	21.8%
107	800	810	805	2.30	7.90	490	500	495	55	55	55	0.90	1.38	5.2	2.42	20.0%
108	690	710	700	0.90	3.87	490	500	495	55	55	55	0.90	1.38	4.88	2.23	17.4%
109	750	740	745	1.36	4.1	490	500	495	55	55	55	0.90	1.38	4.82	1.9	10.8%
110	635	630	632.5	1.31	3.8	490	500	495	55	55	55	0.90	1.38	5	1.6	4.4%
111	650	610	630	0.85	3.8	490	500	495	55	55	55	0.90	1.38	4.94	1.48	2.0%
112	680	670	675	1.41	6.3	490	500	495	55	55	55	0.90	1.380	5.000	1.420	0.8%
113	680	690	685	1.66	7.4	480	500	490	60	60	60	0.82	1.380	4.940	2.340	19.4%
114	750	780	765	1.90	10.0	500	500	500	60	60	60	0.90	1.380	4.900	3.400	41.2%
115	830	810	820	0.88	4.5	500	500	500	60	60	60	0.90	1.380	5.100	3.700	45.5%
116	850	800	825	0.8	4.16	500	500	500	59	57	58	0.92	1.380	4.900	1.780	8.2%
117	820	825	822.5	0.8	4.31	495	500	497.5	60	58	59	0.89	1.380	5.100	2.100	14.1%
118	830	840	835	0.69	4.41	500	500	500	60	60	60	0.90	1.380	5.260	5.580	79.8%
119	850	850	850	0.6	9.50	500	500	500	60	60	60	0.90	1.380	5.000	4.440	61.2%
120	810	775	792.5	1	3.8	495	500	497.5	58	60	59	0.89	1.380	5.000	3.260	37.6%
121	820	800	810	1.54	4.2	500	500	500	60	60	60	0.90	1.380	4.860	3.240	38.3%
122	860	850	855	0.7	4.3	500	500	500	60	60	60	0.90	1.380	5.100	3.720	45.9%
123	870	860	865	0.4	4.3	500	500	500	60	60	60	0.90	1.380	5.240	5.820	84.7%
124	880	900	890	0.7	5.3	500	500	500	60	60	60	0.90	1.380	4.900	4.800	69.8%

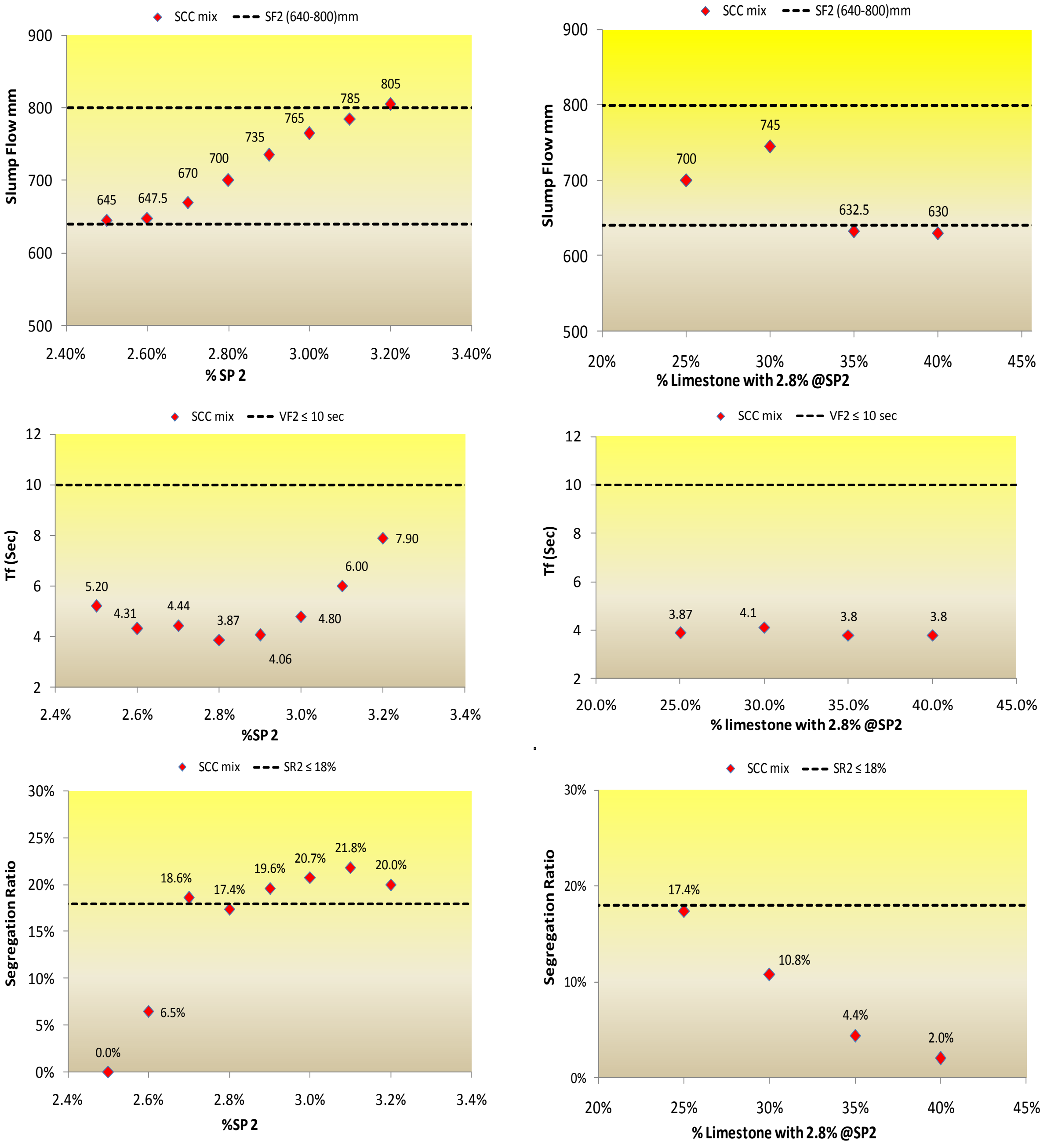

Figure H.1: SCC property results relative to SP and limestone percentage using SP2 optimum dosage on C4

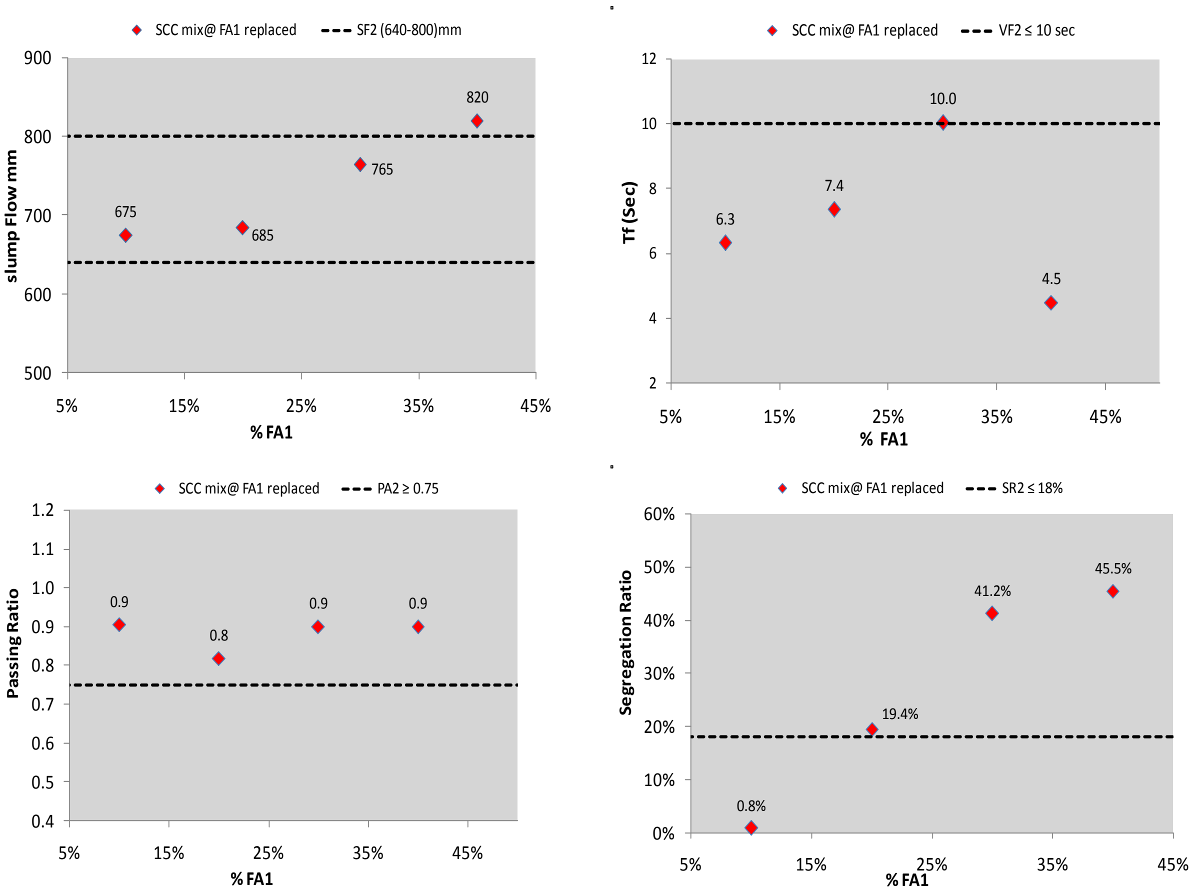

Figure H.2: Effect of replacing C4 with FA1 on SCC properties at sufficient SP2 concentration

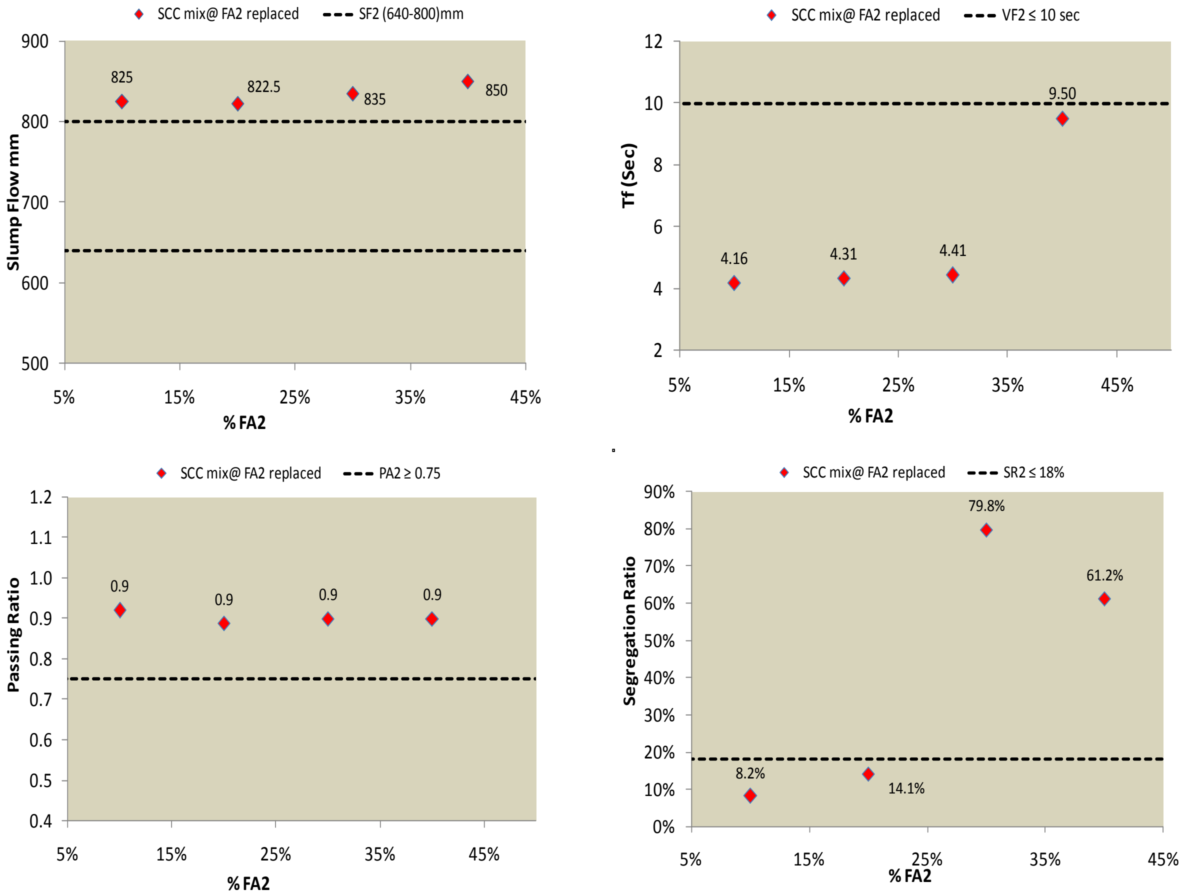

Figure H.3: Effect of replacing C4 with FA1 on SCC properties at sufficient SP2 concentration

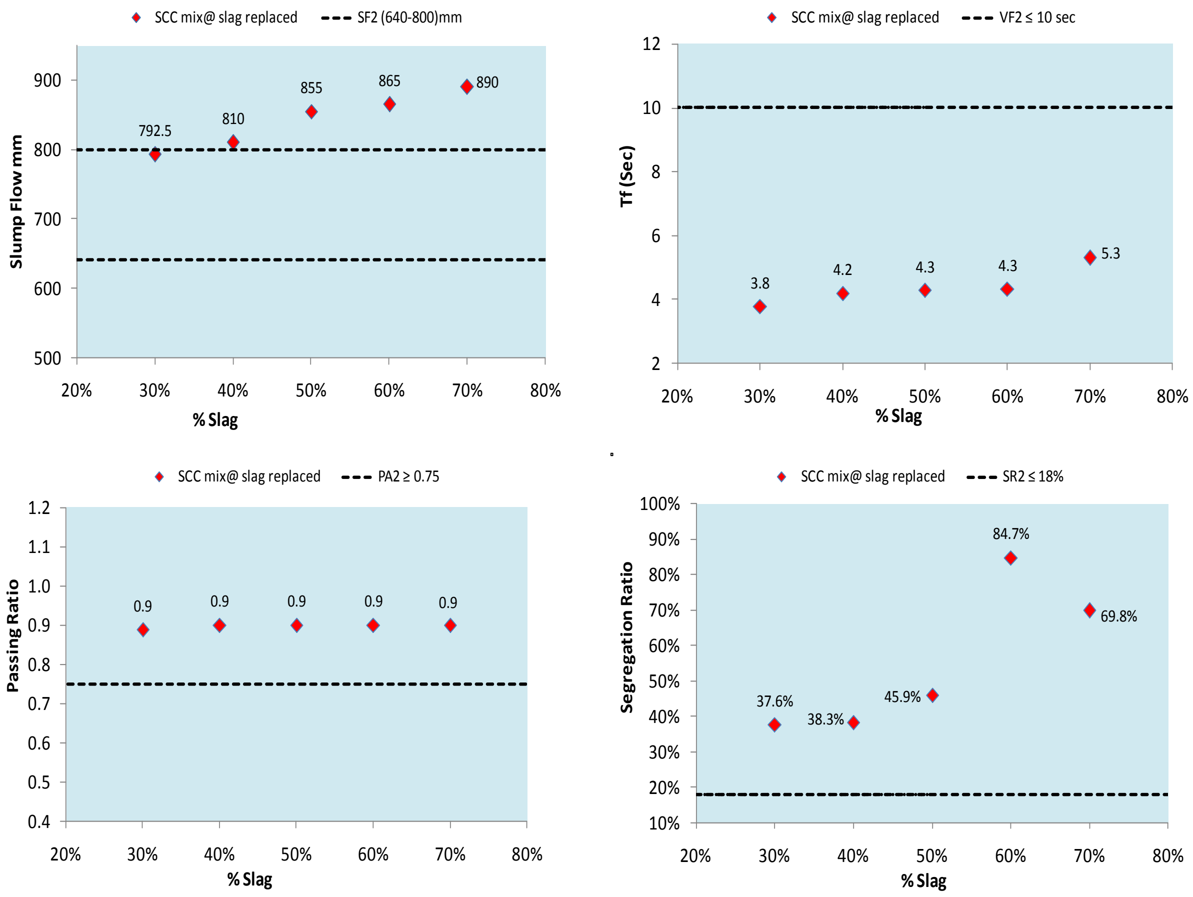

Figure H.4: Effect of replacing C4 with slag on SCC properties at sufficient SP2 concentration

Appendix I. Interaction of FA2 with cement compounds

- Figure I.1: Interaction of extender FA2 with cement compounds C_3A and C_3S on SCC properties using SP1
- Figure I.2: Interaction of extender FA2 with cement compounds, alkali content and surface area on SCC properties using SP1
- Figure I.3: Interaction of extender FA2 with cement compounds C_3A and C_3S on SCC properties using SP2
- Figure I.4: Interaction of extender FA2 with cement compounds, alkali content and surface area on SCC properties using SP2

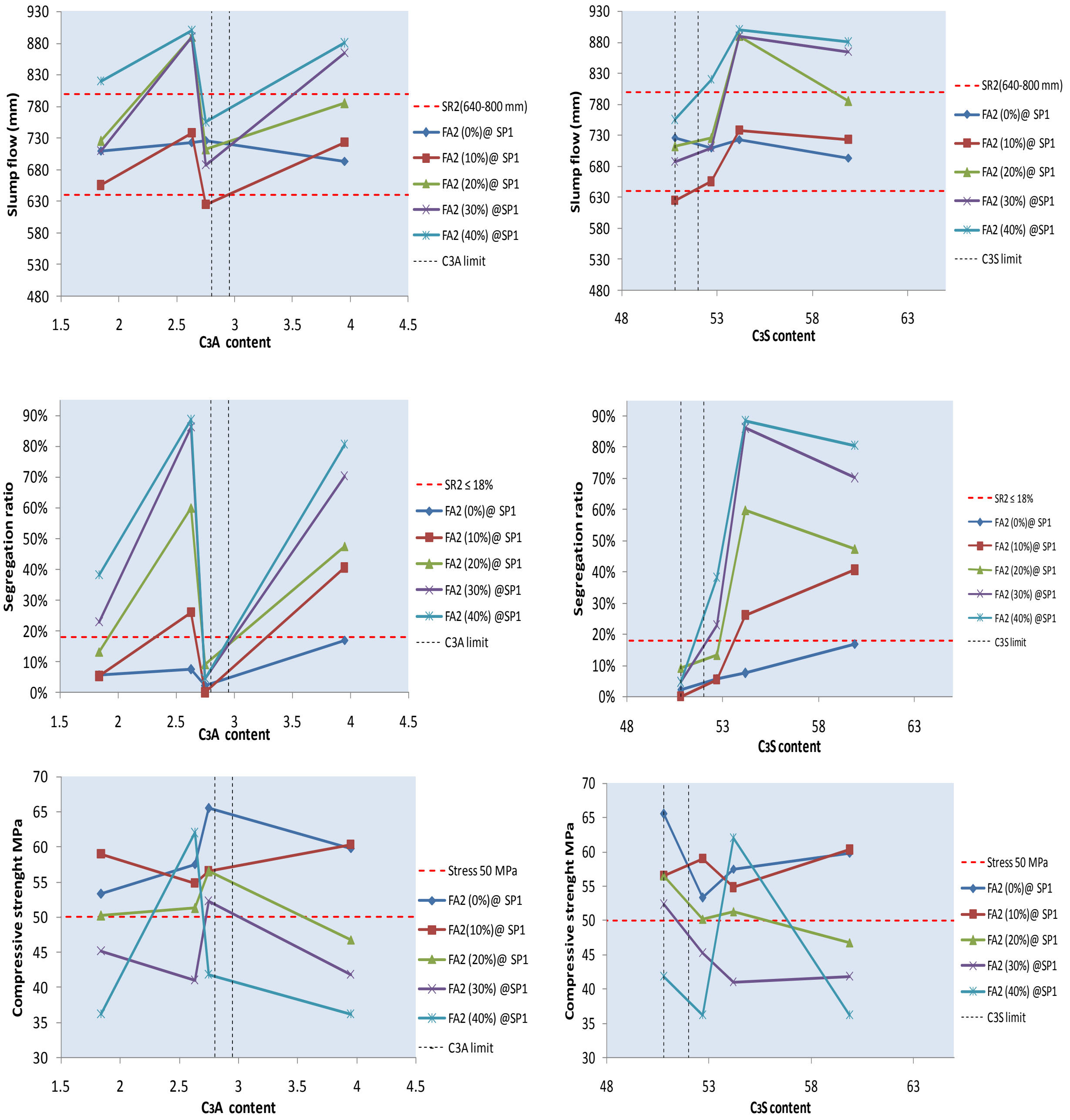

Figure I.1: Interaction of extender FA2 with cement compounds C_3A and C_3S on SCC properties using SP1

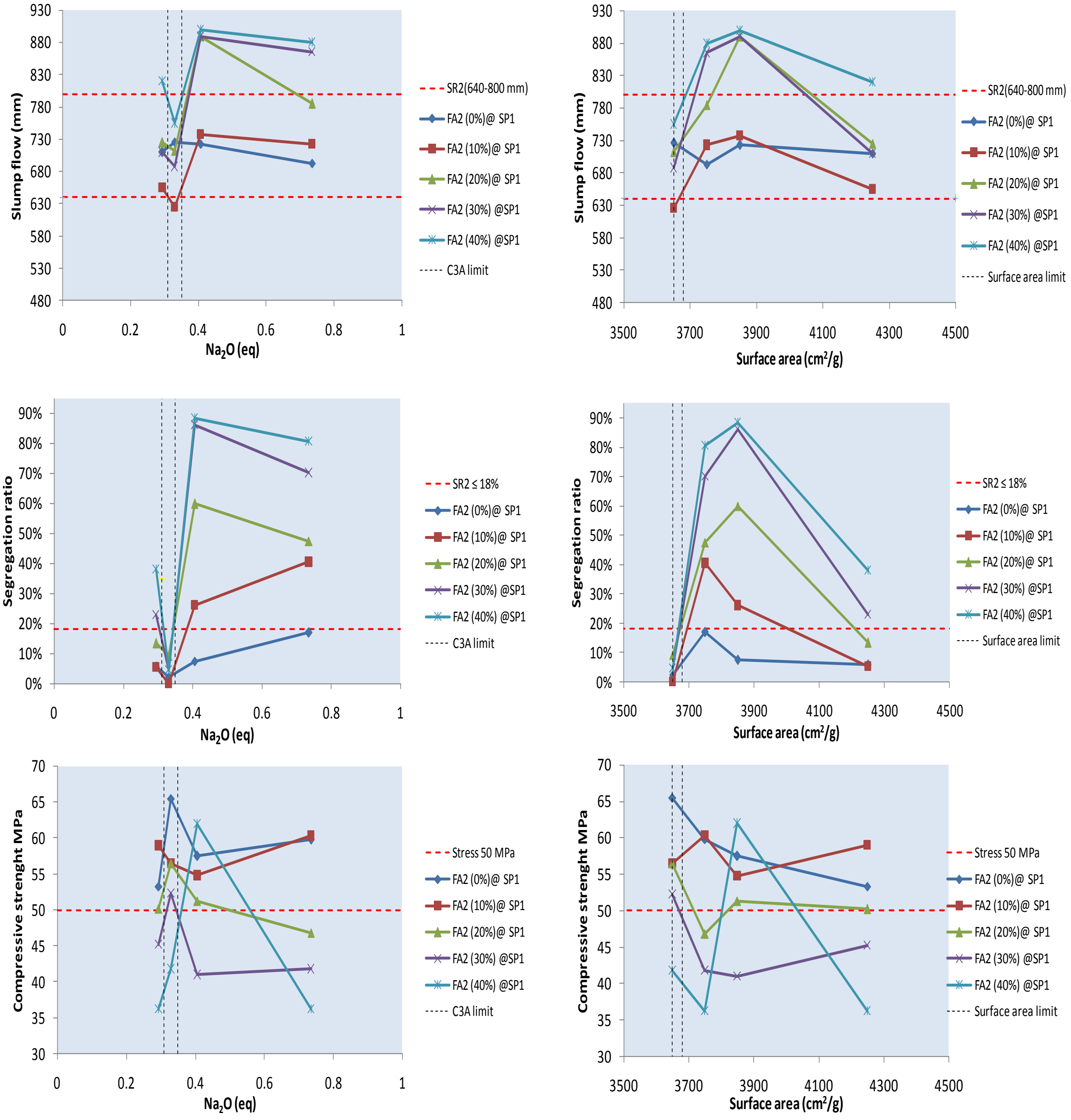

Figure I.2: Interaction of extender FA2 with cement compounds, alkali content and surface area on SCC properties using SP1

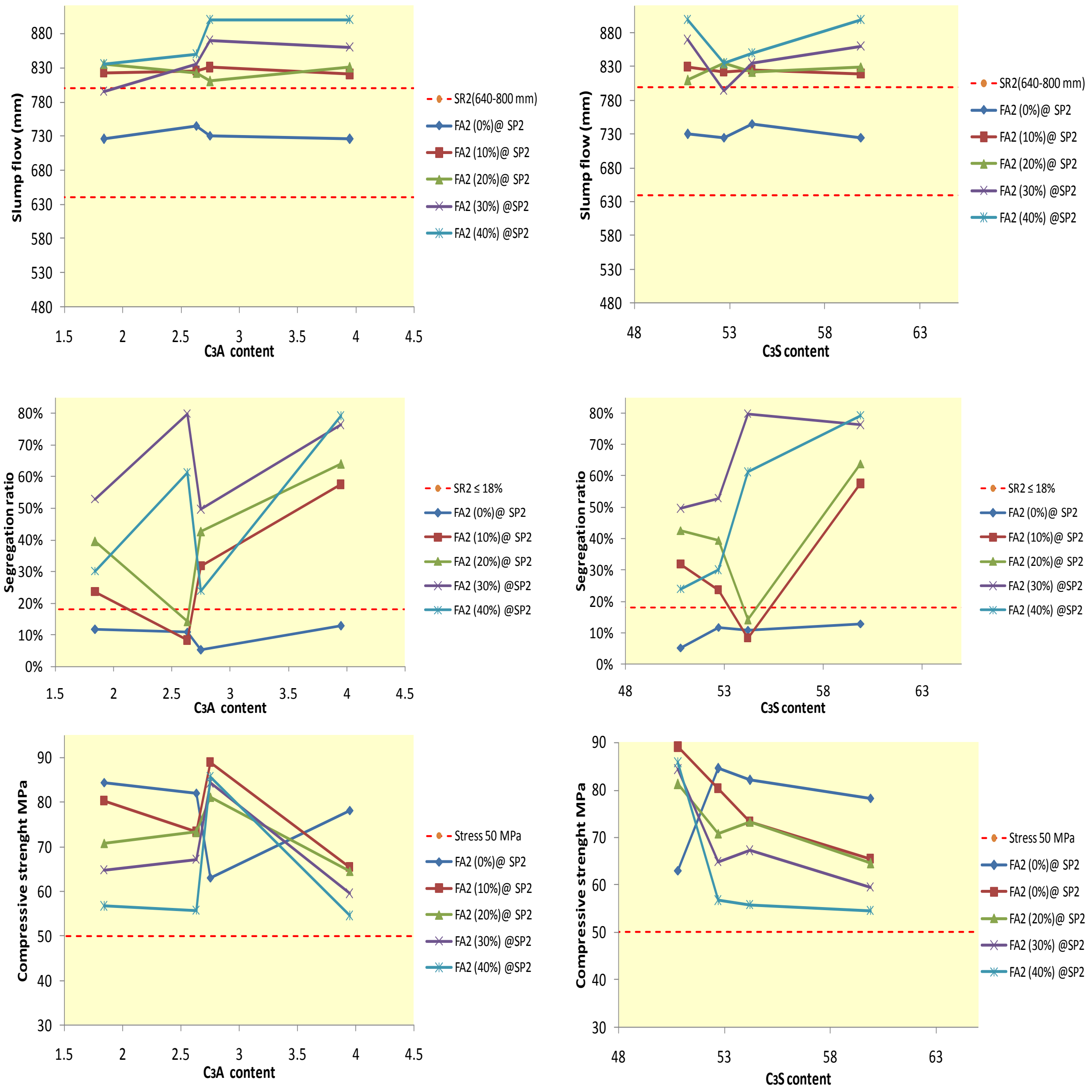

Figure I.3: Interaction of extender FA2 with cement compounds C_3A and C_3S on SCC properties using SP2

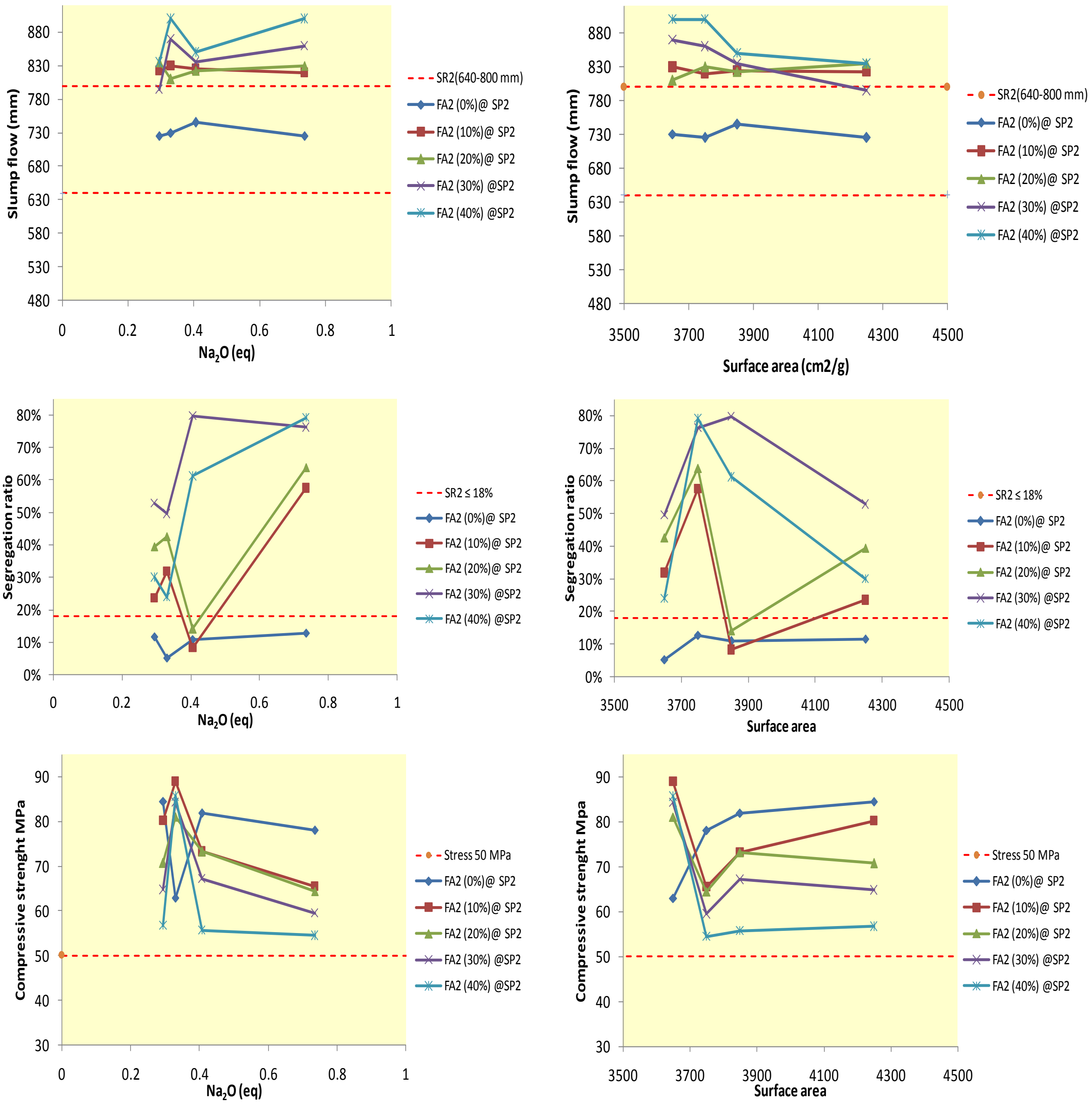

Figure I.4: Interaction of extender FA2 with cement compounds, alkali content and surface area on SCC properties using SP2

Appendix J. Interaction of slag with cement compounds

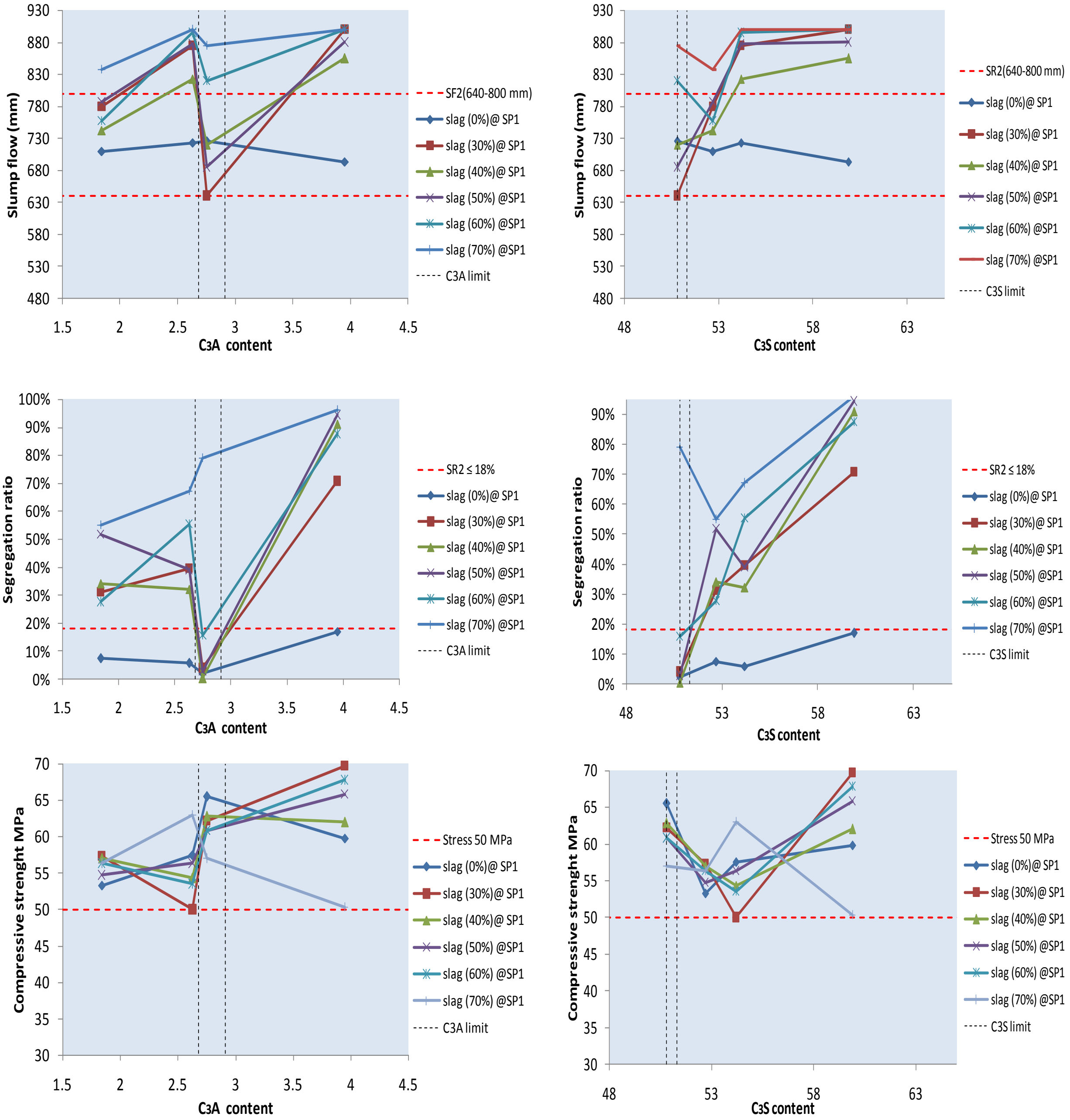

Figure J.1: Interaction of extender slag with cement compounds C_3A and C_3S on SCC properties using SP1

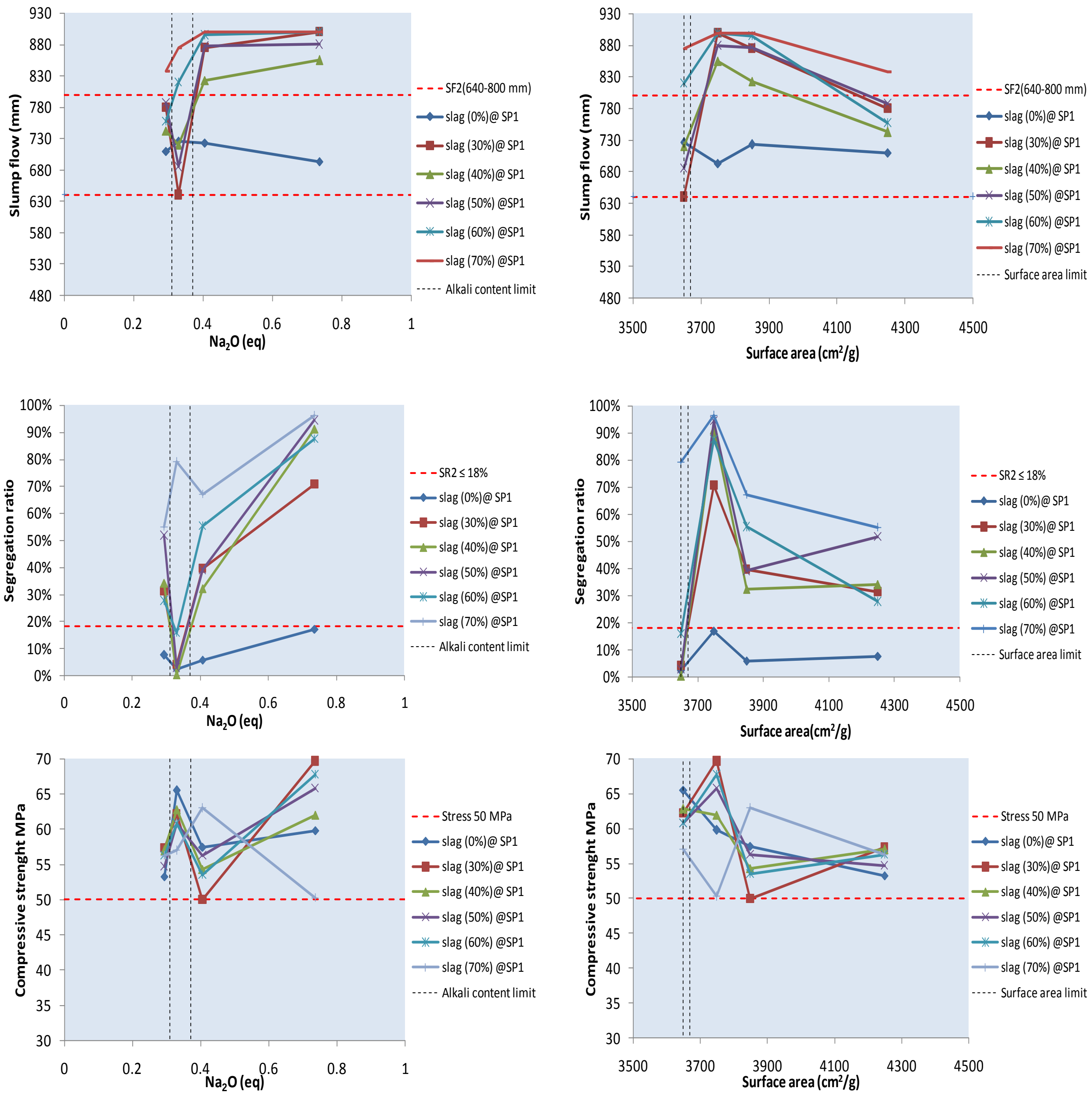

Figure J.2: Interaction of extender slag with cement compounds, alkali content and surface area on SCC properties using SP1

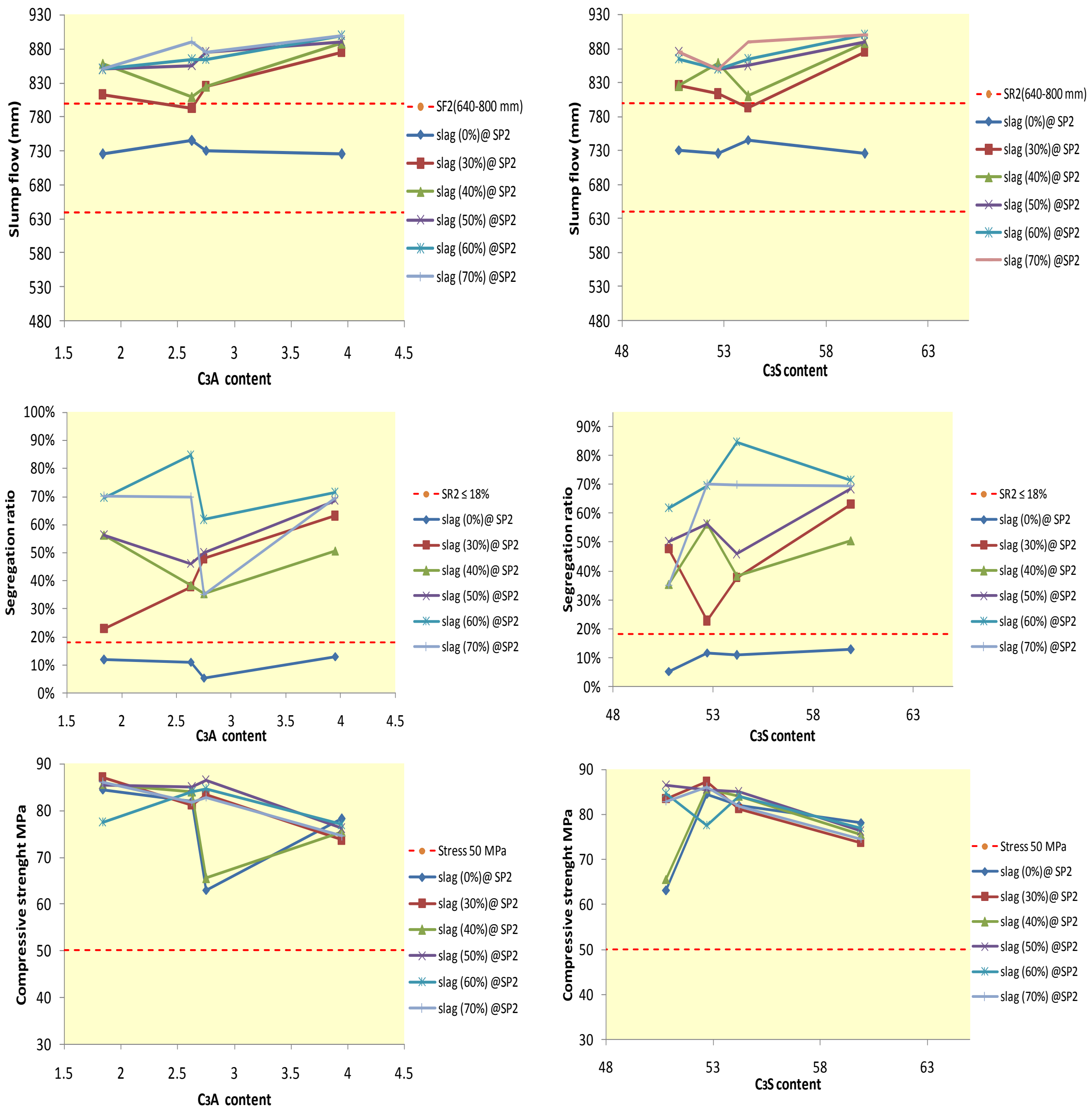

Figure J.3: Interaction of extender slag with cement compounds C_3A content and C_3S on SCC properties using SP2

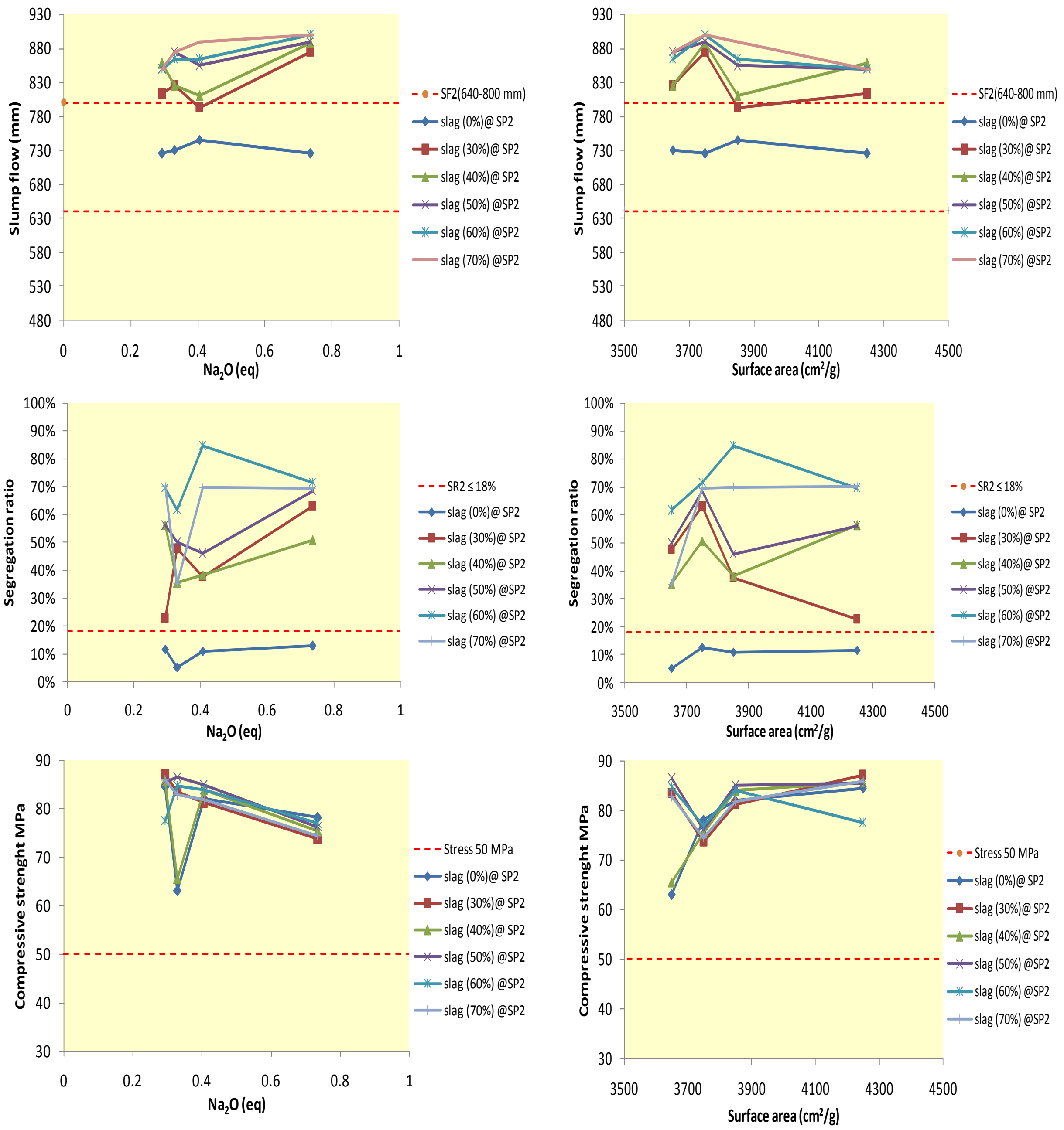

Figure J.4: Interaction of extender slag with cement compounds, alkali content and surface area on SCC properties using SP2