THE FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

DEPARTMENT OF CIVIL ENGINEERING

# Alkali-Aggregate Reaction in Western Cape Concrete

**Prepared by**: Zubair LALL MAHOMED
**Supervised by**: Prof Mark ALEXANDER
**Date of submission:** 18th February 2018

A dissertation submitted to the Department of Civil Engineering, University of Cape Town in partial fulfilment of the requirements for the degree of Master of Science in Structural Engineering and Structural Materials Specialisation

CoMSIRU Concrete Materials and Structural Integrity Research Unit

# Plagiarism declaration:

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own. This thesis/dissertation has been submitted to the Turnitin module (or equivalent similarity and originality checking software) and I confirm that my supervisor has seen my report and any concerns revealed by such have been resolved with my supervisor.

i) I know that plagiarism is wrong. Plagiarism is using another’s work and to pretend that it is one’s own.
ii) I have used the Harvard Convention for citation and referencing. Each significant contribution to, and quotation in, this report from the work, or works of other people has been attributed and has been cited and referenced
iii) This report is my own work.
iv) I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as his or her own work
v) I acknowledge that copying someone else's assignment or essay, or part of it, is wrong, and declare that this is our own work.

Student number: LLLMUH002
Surname: LALL MAHOMED

Signature: Signed by candidate Date: 18th February 2018

# Acknowledgements

The author would like to thank and acknowledge with gratitude the following persons, and companies who made significant contribution towards the completion of this dissertation.

- The supervisor, Emeritus Professor Mark Alexander, for his continuous support, encouragement, guidance and continual academic and technical assistance throughout the course of this dissertation.
- Professor Hans Beushausen, for providing advice over the duration of this study.
- The director of the Concrete Materials and Structural Integrity Research Unit (CoMSIRU), Professor Pilate Moyo, as well as the members of the unit for providing useful suggestions and constructive criticism.
- Mr Steve Croswell, from Portland Pretoria Cement Ltd (PPC), for their advice and donations used in this research.
- The administration staff of the department of civil engineering for their assistance with administrative matters related to this research.
- Mr Nooredien Hassen, the civil engineering concrete laboratory manager, for his assistance and guidance with the laboratory-related experimentation.
- Mr Tahir Mukkadam, senior technical officer, for his assistance with laboratory-related experimentation.
- Mr Charles Nicholas, the civil engineering workshop principal technical officer, for manufacturing the equipment required for the experimentation work.
- The departmental assistant Mr Leonard Adams, the civil engineering concrete laboratory staff, Mr Chris Caesar, Mr Elvino Witbooi and Mr Charlie May and the wastewater research laboratory assistant Mr Hector Mafungwa, for their help with experimental work when needed.
- The postgraduate students in civil engineering, especially Mr Nabeel Omar, for a priceless friendship and constant support throughout this journey.
- Family, especially Mrs Nawsheen Lall Mahomed, and friends for their continual support and love.

The author would also like to thank and acknowledge the financial support from CoMSIRU throughout the duration of the dissertation.

# Abstract

Alkali-aggregate reaction, AAR, was first discovered in 1938 by Stanton in the USA. Subsequently, researchers across the globe have reported incidences of the reaction with different aggregates in their respective countries. The reaction entails the interaction between reactive silica found in aggregates and alkali in the pore solution of concrete. Through research, the reaction has been categorised into three main classes depending on the type of aggregate used. Alkali-silica reaction, ASR, being one of those classes, is the most common one and is the primary concern in the local concrete industry in the Western Cape, where reactive greywacke aggregates are used.

In South Africa, the problem has often been dealt with using low alkali cement. However, those low alkali resources have been depleted and more alkali-rich resources are now being used in the production of cement. This completes the three requirements needed for ASR reaction to occur, namely a high alkali source, presence of reactive silica and moisture conditions. Furthermore, the introduction of greywacke crusher sand as a partial substitute to natural sands in local concrete mixes, implies that more reactive silica is available in the mixes. The research aims at finding whether the current concrete mixes are prone to alkali silica reaction and how to mitigate this expansion using cement extenders, which is the most common ASR mitigation measure. The long-term performance test, which allows testing of concrete, generally takes a minimum of 6-12 months to complete. As such, attention was turned towards the use of an accelerated mortar bar test (AMBT), which is generally used as an indicator test in the preliminary stages of the testing. However, the AMBT test imposes material limitations such as cement type and aggregate grading. Consequently, modifications were made to the AMBT test to allow for the concurrent use of reactive fine aggregates and coarse aggregate as well as a commercial cement.

The first stage of this project involved the use of a modified AAR-2 AMBT test and was subdivided into three phases. Phase A was centred around investigating the use of reactive fine aggregates and reactive coarse aggregates in conjunction. For this purpose, 40% of the total aggregate blend by mass was constituted of a sand blend having both reactive (greywacke) and non-reactive (Philippi dune sand) components, while the remaining aggregate portion was a 9.5 mm greywacke coarse aggregate. The reactive fine aggregate level was varied in the sand blend and the ASR expansion recorded. A limited pessimum effect was observed at around 40-60% reactive greywacke by mass in the sand blend, whereby the expansion recorded peaked. Phase B of Stage 1 then involved the use of a 50/50 greywacke crusher sand/Philippi dune sand in the sand blend as a base mix. Cement extenders were then substituted in different levels for the cement. For this work, common replacement levels of 20, 30 and 40 percent fly ash and 40, 50 and 60 percent corex slag were used. It was found that all the mixes mitigated the ASR expansion to acceptable levels, that is below the 0.10% expansion, while increasing cement extender levels reduced the expansion further. It was also found that fly ash was more effective at reducing ASR than corex slag. Phase C of Stage 1 involved identifying the mechanisms behind which cement extenders mitigate ASR. Subsequently, the mixes used in Phase B were replicated with the exception that an inert limestone filler, “Kulubrite 10”, was used instead of the reactive cement extenders. It was observed that the limestone filler does reduce the expansion but to a much lesser extent than the reactive cement extenders. This implied that the cement extenders not only dilute the alkali content but also undergo further reaction which removes more alkali from the pore solution.

The second stage of the project dealt with the influence of ASR gel formation on compressive strength. Compressive strength tests were performed on 2 sets of cubes for each mix, which were exposed to different curing conditions, namely a water bath at 22-25℃ and an alkaline solution of 1M NaOH at 80℃. It was observed that there is reduction in strength as the expansion increases. Scanning electron microscopy, SEM, performed in Stage 3, of the samples confirmed that this phenomenon is due to the increased number of cracks as the expansion increases. Other subsidiary tests conducted in Stage 3, such as light microscopy and EDS, resulted in inconclusive results and need to be further investigated.

Lastly, Stage 3 involved conducting long-term testing using a modified version of the AAR-4 test and field performance test. Five ‘real-life’ concrete mixes, based on the mixes in Stage 1, were cast and are still under observation. The initial measurements on the AAR-4 samples showed no sign of expansion as of 15 weeks of testing. This was thought to be due to the un-boosted alkali content of the cement, 0.7 % $Na_2O$ eq, which may have not been enough to start the reaction. The preliminary results of the field testing at 15 weeks of age showed that apparent shrinkage was occurring, likely due to the environmental influences over this period (summer months). This could be attributed to the fact that the ASR gel formation mechanism is still in its early stages in those specimens or has not started yet. The final results of these tests, at 6 months and 2 years respectively, are however needed to confirm whether the modifications made in Stage 1 of this research resulted in a good approximation of what is to be expected from the use of reactive greywacke fine and coarse aggregates in conjunction.

In general, it can be concluded that the concurrent use of reactive greywacke crusher sand and reactive greywacke coarse aggregate in concrete mixes, would not be deleterious to structures. Nevertheless, it is advised that a minimum of 20% fly ash or 40% ground granulated corex slag by mass of the total binder content is used, as per the current conventional precautions.

# Abbreviations and symbols

| | |
|---|---|
| AAR | Alkali-aggregate reaction |
| ACR | Alkali-carbonate-rock reaction |
| AMBT | Accelerated mortar bar test |
| ASR | Alkali-silica reaction |
| CPT | Concrete prism test |
| CSH | Calcium silica hydrate |
| EDS | Energy dispersive spectroscopy |
| FA | Fly ash |
| GGBS | Ground granulated blast furnace slag |
| GGCS | Ground granulated corex slag |
| ICAAR | International conference on alkali-aggregate reaction |
| ICP-OES | Induced coupled plasma – optical emission spectroscopy |
| $Na_2O$ eq | Sodium equivalent |
| S | Slag |
| SEM | Scanning electron microscopy |
| SCM | Supplementary cementitious materials |
| SF | Silica fume |
| w/b | Water to binder ratio |

# Table of contents

# List of figures

# List of tables

# 1 Introduction

## 1.1 Background to the research problem

Alkali aggregate reaction, hereafter referred to as AAR, is a problem reported all over the world in existing concrete structures. The problem was first observed by Stanton in the USA in the 1938. Following that, Stanton continued with research on the topic in the 1940s (Blight & Alexander 2011). However, until now many of the papers produced on the topic have been from a scientific perspective. AAR is basically an adverse chemical reaction between the alkalis in the concrete matrix and the reactive compounds of the aggregates. The major issue with this reaction is that the visible effects of the reactions only appear years after construction. By then, the effects may be too severe and structural integrity may be compromised.

The reaction itself can be classified into three main categories namely; alkali-silica reaction, alkali-silicate reaction and alkali-carbonate-rock reaction, depending on the nature of the aggregates (Alexander & Mindess 2005). Zooming in on a local perspective, the two main types of aggregates being used in the Western Cape are Greywacke and Granite, both of which consist mostly of quartz (Grieve 2009), and therefore, alkali silica reaction, hereafter referred to as ASR, would be the primary concern in the region.

ASR was reported by Helmuth and Stark in 1992 to involve two types of gel products, namely a non-swelling calcium-alkali-silicate-hydrate (C-N(K)-S-H) and a swelling gel alkali-silicate-hydrate (N(K)-S-H). The reaction is deemed safe if only the non-swelling gel is formed but unsafe if both are formed. The latter occurs only when three conditions in the concrete are met simultaneously. Firstly, a sufficient amount of alkali, generally believed to be greater than 0.6 percent in terms of sodium oxide equivalent, should be present in the concrete. Secondly, a reactive form of silica in sufficient quantity is required which is generally the aggregates. Finally, a sufficient source of moisture is required for ASR to occur (Oberholster 2009). Consequently, restricting one of the aforementioned conditions would be enough to prevent the reaction from occurring.

In South Africa, the problem has been dealt with largely through the use of low alkali cements, that is, cements having sodium oxide equivalent lower than 0.6% in their chemical composition. However, the low alkali resources used to make these cements have been significantly depleted and higher alkali content resources are currently being used in cement production leading to a possible resurgence of the ASR problems. Furthermore, due to resource depletion of natural sands, crusher sands, which are basically rock ground to fine aggregate particle sizes, are now being used as a substitute to natural sands. In the Western Cape, crusher sand made from Greywacke is now being utilised in the construction industry, therefore increasing the amount of reactive silica in the concrete mixes. The use of supplementary cementitious materials, SCMs, which generally cause a reduction in ASR by diluting the releasable alkalis or alkali binding mechanisms, is therefore the more viable option forward. (Thomas et al. 2006).

## 1.2 Problem to be investigated

It is known that greywacke as an aggregate is reactive in terms of alkali silica reaction (Grieve, 2009). However, the effect of the partial or complete use of greywacke as fine aggregate, in mixes containing reactive greywacke as coarse aggregate, on ASR potential is not documented. Moreover, it is unknown whether the current cement extender levels employed in the construction industry is sufficient to mitigate the expansion associated with the increased amount of reactive aggregates.

## 1.3 Research aims and objectives

The aim of this research is focused on identifying the susceptibility of concrete mixes currently being used in the Western Cape to AAR. Based on the trends described in the background above, the following objectives were set up:

- Experimentally determine the effect of adding greywacke crusher sand using a wide range of ‘micro-concrete’ mixes (refer to Section 1.5) with different replacement levels of crusher sand;
- Use the ‘worst case scenario’ mix, i.e. the one exhibiting the highest expansion, to experimentally determine the amount of SCMs required to mitigate the ASR expansion to acceptable levels;
- Experimentally determine the mechanism through which the SCMs can mitigate ASR expansion; and
- Critically evaluate the results obtained and formulate recommendations for current practice, if required.

## 1.4 Key research questions

From these general objectives, the following research questions were formulated:

- Is there a concern in using crusher sand over natural sands in terms of ASR?
- Is there a threshold for crusher sand at which the reaction starts occurring?
- Is there a critical content of crusher sand and coarse aggregate at which the expansion is maximum or does the latter increase linearly with increasing aggregate?
- Does the addition of additional quantities of reactive aggregate cause a better dispersion of reaction products or are they still concentrated around larger coarse aggregate particles?
- Is there a threshold at which each SCM (fly ash and GGCS) limit the adverse effect, if any, of using Greywacke as crusher sand? If so, what are those limits?
- Do the reduction mechanisms of SCMs (that is dilution effect and reaction effect) produce marginal differences or is one of them much more significant than the other to the point where one or the other may be considered negligible?

## 1.5 Scope and limitations

As previously mentioned there are three main factors causing ASR in concrete mixes and restricting any of these three would mitigate the adverse reaction. As such, it is necessary to define the scope and identify the limitations of this research as it is not possible to include all the mitigation measures in this research. The scope of this research is to determine the effect of adding reactive crusher sand in concrete mixes, already containing reactive coarse aggregates, on ASR potential and whether current mitigation measures, that is the use of supplementary cementitious materials, is enough to mitigate the reaction.

The limitations of the research are listed herein:

- The number of mixes which are to be investigated using the AMBT test was limited to 21 as one test takes roughly 1 month to complete and the laboratory facilities can only accommodate this many over the specified period of the study;
- The materials will be restricted to only the most commonly used materials in the construction industry in the Western Cape;
- Only greywacke coarse aggregate will be used in conjunction with the crusher sand as granite is less reactive in terms of ASR and therefore the worst-case scenario will be investigated;
- The mixes will be designed as 'micro-concrete' for the AMBT test. The AMBT test generally only makes use of fine aggregate or crushed coarse aggregates to fine fractions. The introduction of a 9.5mm reactive greywacke coarse aggregate as 60% of the total aggregate content effectively results in the mix being considered as a 'micro-concrete' instead of a mortar. The remaining 40% will be a blend of reactive greywacke crusher sand and non-reactive Philippi dune sand;
- The accelerated mortar bar tests which are commonly used in ASR testing will need to be slightly modified for this study, this include the use of a commercial cement and a bigger mould size;
- The number of samples tested for the subsidiary test, i.e optical microscopy, SEM, EDS and ICP-OES, would be limited as these tests were only performed on a qualitative basis to supplement the results from the main tests;
- The long-term performance test will be limited to 5 mixes as the laboratory facilities can only accommodate this many over the period of testing; and
- Only preliminary results of the long-term performance test will be provided in this dissertation as the formulation of the mixes and testing period exceeds the duration of this degree.

## 1.6 Thesis outline

The document starts with an introduction (Chapter 1) to the research whereby the background of the research problem, the aims and objectives and the key research questions are clearly established. The scope and limitations of the research are also listed. Consequently, the second section (Chapter 2) provides a review of the relevant literature associated with the study. This section starts by providing a general overview of the alkali aggregate reaction. The focus is then brought to alkali silica reaction which is the main concern in the Western Cape. This entails a detailed explanation of the mechanisms of the reaction, the factors influencing ASR and mitigation measures. A review on the effect of particle size on ASR expansion is then provided followed by lastly a review of the main tests which are used to assess ASR potential of aggregates and concrete mixes. Chapter 3 deals with the experimental techniques involved in this research. The experimental work is subdivided into 4 stages. The first stage involved assessing the ASR potential of the different mixes containing varying levels of reactive aggregate or cement extenders using a modified AAR-2 AMBT test. Stage 2 of this research involved assessing the impact of ASR gel formation on the compressive strength of concrete. Stage 3 provides subsidiary test methods which were employed to supplement the results of the main tests. Finally, Stage 4 of the testing regime discusses the use of long term performance test to validate the results obtained from the AMBT test. The results obtained from the experimentation are then presented and discussed in Chapter 4. An overall discussion is then presented in Chapter 5 whereby conclusions and recommendations are also formulated. A list of references used in this research is then provided in Chapter 6. Finally, relevant detailed experimental results are presented in the Appendix. The thesis outline is schematically depicted in Figure 1-1.

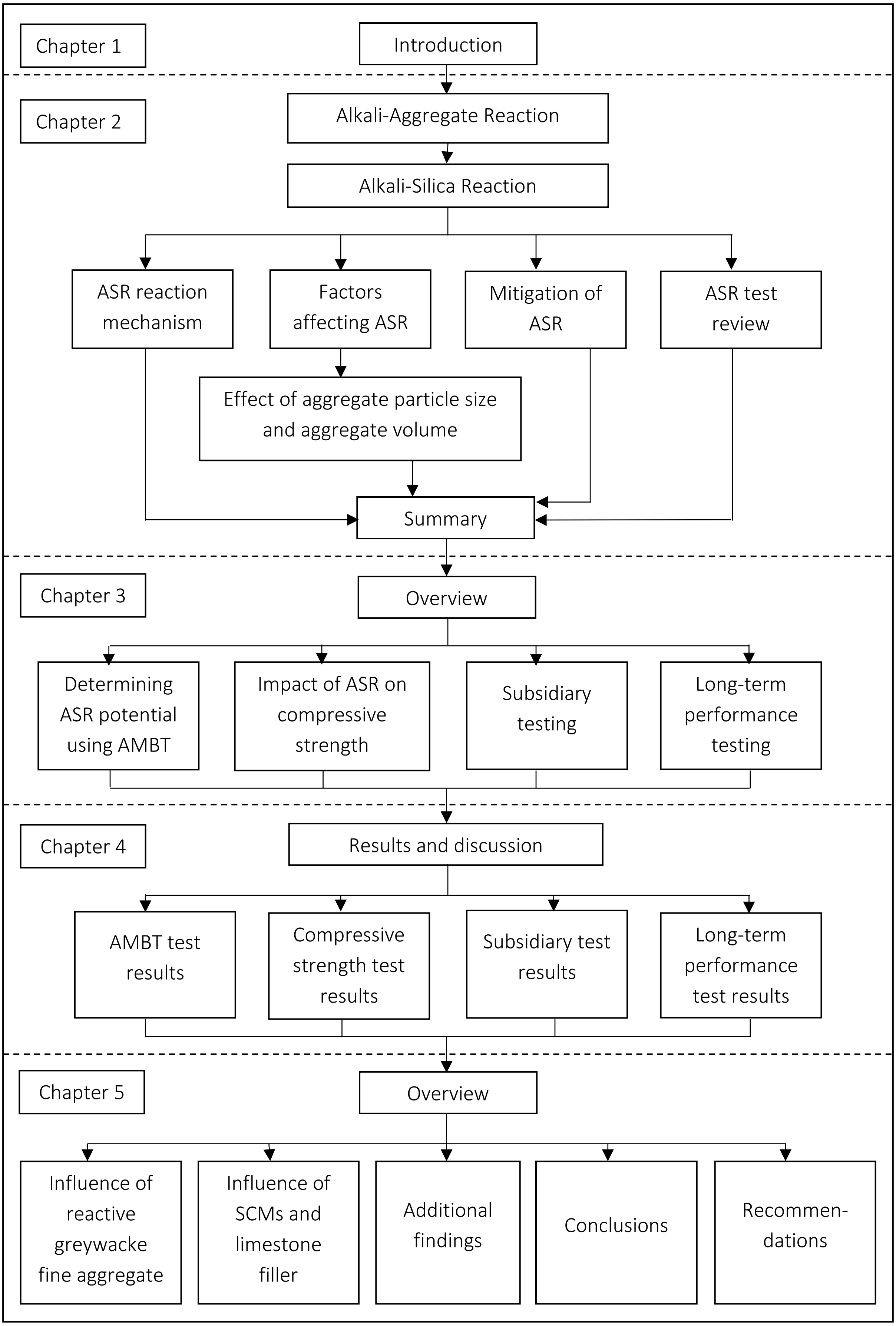

*Figure 1-1: Thesis outline*

# 2 Literature review

## 2.1 Overview of chapter 2

This chapter provides a review of the literature on the topic of alkali aggregate reaction, AAR, with emphasis on alkali silica reaction, ASR. A brief overview of alkali aggregate reaction is provided in Section 2.2, which includes the origin and different forms of the reaction. The focus will be brought more towards the main issue of the research which is alkali silica reaction in Section 2.3. Subsequently, Section 2.3 will be broken down into subsections, each detailing an aspect of the ASR process. Lastly, Section 2.4 will provide a summary of the literature review presented in this chapter.

## 2.2 Overview of alkali aggregate reaction

### 2.2.1 Definition

Alkali aggregate reaction, AAR, is an adverse chemical reaction which occurs between alkalis in the pore solution and certain mineral constituents of aggregates present in concrete. The reaction generally leads to cracking and cause distress within the concrete element (Oberholster 2009).

### 2.2.2 Historic background of AAR

The reaction was first discovered by Thomas Stanton of the California Division of Highways in the United States of America in 1938. The phenomenon was then documented in a report published in the Engineering News Record in February of 1940. Consequently, a paper by Stanton, which is regarded as the first definitive work on ASR, was published by the American Society of Civil Engineers in December of 1950 (Thomas 2011). Since then, researchers across the globe have also reported cases of alkali aggregate reaction in their respective countries. In South Africa, AAR was first reported in structures in the Cape Peninsula in the 1970s. Since AAR directly affect not just durability properties but also mechanical properties of concrete, studies to prevent the process has gained momentum over the years. The first international meeting, International Conference on Alkali-Aggregate Reaction (ICAAR), dedicated to the issue was convened in Denmark in 1974. Since then, the conference is held every four years, the latest of which (15th ICAAR) was held in Brazil in 2016, whereby researchers across the world are encouraged to present their research work on AAR.

Locally, AAR was thoroughly investigated over a period of 15 years since its discovery in 1970s. The reaction was identified in numerous structures, ranging from small structures such as pile caps to massive structures such as dams, in different parts of the country. However, research on the topic stagnated in the 1980s and since then most information on AAR has been derived from international studies (Oberholster 2009).

### 2.2.3 Types of AAR

Based on the studies conducted throughout the world, it was found that AAR can be classified into three main categories; namely alkali-silica reaction, alkali-silicate reaction and alkali-carbonate-rock reaction, depending on the nature of the aggregates which are involved in the process.

#### 2.2.3.1 Alkali-silica reaction

Alkali-silica reaction, hereafter referred to as ASR, is a reaction occurring between the alkaline pore solution of the concrete and metastable forms of silica, such as volcanic glasses, cristobalite, tridymite and opal, found in the aggregates. ASR can also refer to the reaction between the pore solution and aggregates containing or comprising of cherts, chalcedony, microcrystalline quartz, cryptocrystalline quartz or strained quartz. Common rocks consisting of such features are but not limited to: greywacke (strained quartz or microcrystalline quartz), quartzite, hornfels, phyllite, argillite, granite (strained, microcrystalline or cryptocrystalline quartz), granite-gneiss and granodiorite. The reaction process of ASR results in an expansive gel which induces tensile stresses in the concrete and causes cracking (Alexander & Mindess 2005).

#### 2.2.3.2 Alkali-silicate reaction

This terminology was introduced to differentiate ASR from reaction involving aggregates such as greywacke and argillite found in Nova Scotia, Canada. The reaction involves the expansion and exfoliation of certain clay minerals (phyllosilicates). However, there has been no clear evidence provided whether this reaction differs from the conventional ASR mechanism (Alexander & Mindess 2005).

#### 2.2.3.3 Alkali-carbonate reaction

Alkali-carbonate-rock reaction, hereafter referred to as ACR, is a type of AAR limited to carbonate aggregate containing clays such as certain argillaceous dolomitic limestones or argillaceous calcitic dolostones. In this reaction, no gel is produced. However, the coarse aggregates do undergo expansion following the reaction of alkali hydroxides reaction with small dolomitic crystals in the clay matrix. This reaction is referred to as dedolomitisation. It eventually results in cracking caused from tensile stresses produced from the expansion of the aggregates (Alexander & Mindess 2005).

#### 2.2.3.4 South African (Western Cape) context

The two main types of aggregates being used in the Western Cape are greywacke and granite. Consequently, ASR would be the primary concern in the region. Greywacke, more commonly known as the Malmesbury Shale, is a fine-grained, ‘glassy’ rock consisting of mosaic of quartz, feldspar, mica, iron oxides and sometimes alumina silicates. It is to be noted that Greywacke was the first aggregate to be recognised in South Africa of exhibiting ASR and has since been classified as ‘highly reactive’ in terms of ASR. Granite on the other hand includes crystalline igneous and metamorphic rocks of differing grain size and consisting mainly of feldspar and quartz. This type of aggregates was classified as ‘moderately reactive’ in terms of ASR. Nevertheless, due to the lower elastic modulus conferred via the use of granite aggregate, greywacke is still being used extensively in the Western Cape (Oberholster 2009)

## 2.3 Alkali-silica reaction

This section describes the visible characteristics of ASR, the mechanisms via which the reaction occurs, the factors affecting the reaction, deterioration in materials properties due to ASR, mitigation measures associated with ASR and test methods used to evaluate ASR potential.

### 2.3.1 ASR and its visible characteristics

As described above, ASR is a detrimental reaction which occurs between the alkaline pore solution of concrete and various metastable forms of silica present in natural or synthetic aggregates. Hydroxyls ions induces a nucleophilic attack on silica structures which upon degradation behave as a hygroscopic gel. Consequently, the gel swells in the presence of moisture causing tensile stresses within the concrete element. This may eventually lead to cracking of the concrete element if the tensile strength of the latter is surpassed (Blight & Alexander 2011).

The diagnosis of an affected structure may sometimes be misinterpreted as the latter may produce similar visual representation as shrinkage affected structures. However, the following are visible characteristics present only in ASR affected structures:

- Whitish product on the surface of the structure;
- Reaction rims around the aggregates;
- Cracks through the aggregates which are sometimes filled with gel;
- Matrix crack which are continuous with aggregate crack; and
- Voids filled with reaction products.

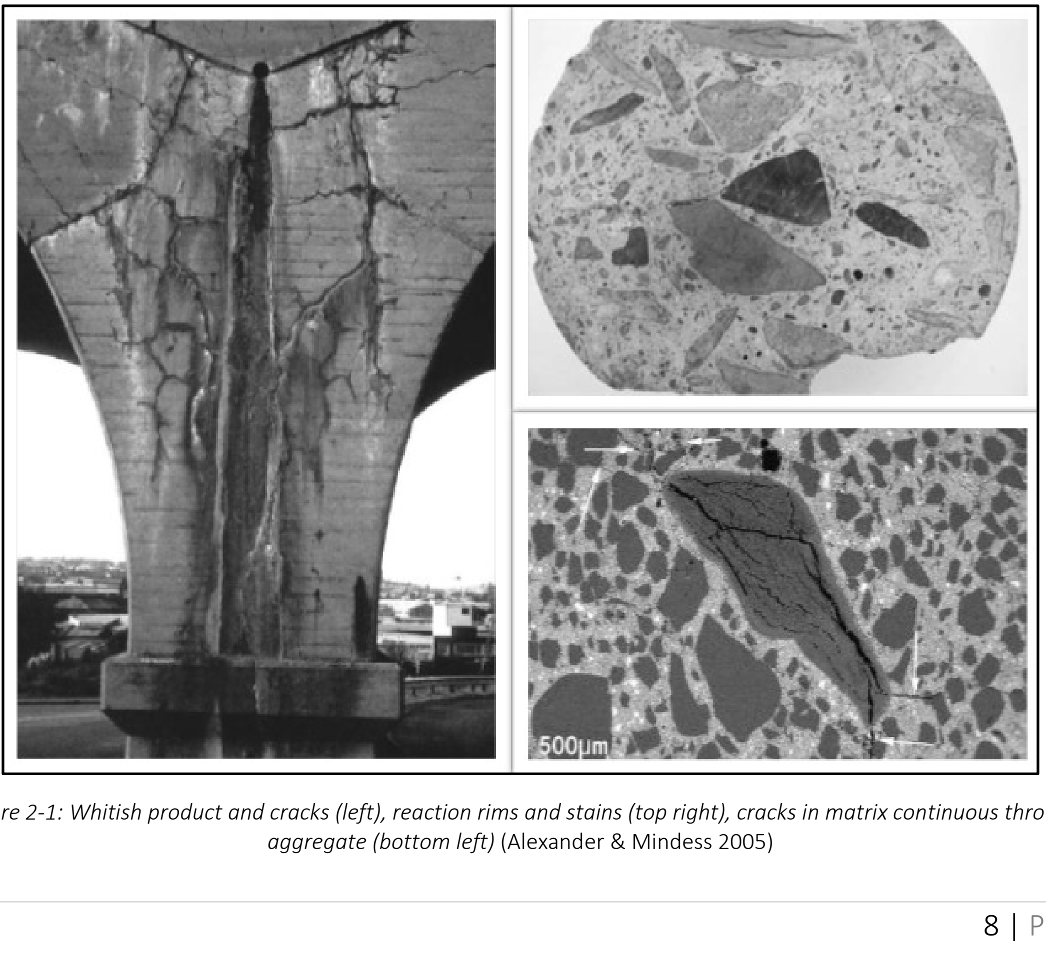

*Figure 2-1: Whitish product and cracks (left), reaction rims and stains (top right), cracks in matrix continuous through aggregate (bottom left)* (Alexander & Mindess 2005)

### 2.3.2 ASR reaction mechanism

To mitigate ASR, the comprehension of the reaction mechanisms involved in the process is essential. Consequently, over the years several studies have been focused on the reaction mechanisms. Subsequently, Helmuth and Stark provided an explanation of the reaction processes in 1992. Several authors have since provided their input on the findings but the general concept is relatively similar. It was found that ASR is a result of a series of reaction processes which occur sequentially. These include the dissolution of metastable silica, the formation of nano-colloidal silica sol, the gelation of the latter and swelling of the gel (Rajabipour et al. 2015).

$$(Si0_2)_{solid} \rightarrow (Si0_2)_{aqueous} \rightarrow (Si0_2)_{sol} \rightarrow (Si0_2)_{gel} \rightarrow swelling\ of\ gel \qquad \text{Equation 1}$$

On the other hand, a highly degraded solid form of silica may change directly into a silica gel if there is limited cross-linking between the silica chains. From the processes mentioned above, the first step which is silica dissolution usually has the slowest rate. As such, it is usually the main factor which governs the rate of ASR in concrete. Additionally, the swelling process of the gel depends on the moisture content and mass transport properties of the concrete.

#### 2.3.2.1 Dissolution of metastable silica

The first step of the chain of reactions which result in ASR damage is the dissolution of metastable silica. Silicates which is one type of metastable silica is one of the most common type of minerals in rocks on Earth. These consist mostly of three-dimensional tetrahedral silica units whereby one Si atom is surrounded by four oxygen atoms. Moreover, the units are connected through siloxane bonds which involves oxygen vertices, also known as bridging oxygens. Furthermore, due to the varying degrees at which the angle of the Si-O-Si bond between the $SiO_2$ tetrahedra, a wide variety of silica structures such as macro-crystalline (Figure 2-2a), micro/nano-crystalline, or amorphous (Figure 2-2b) may occur.

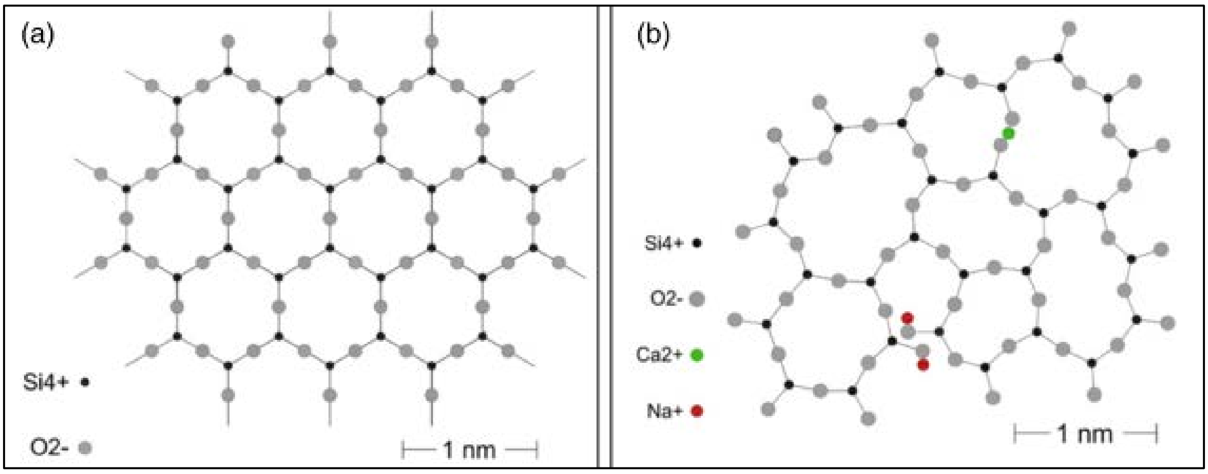

*Figure 2-2: (a) 2D representation of quartz composed of uniformly sized silica rings where all oxygens are bridging silicon atoms (b) amorphous $SiO_2$, showing non-uniform rings and the contribution of alkalis and Ca in forming non-bridging oxygens* (Rajabipour et al. 2015)

The (≡Si-O-) bonds in the structures presented above are very susceptible to hydroxyl ($OH^-$) ions attack in alkaline environments. This results in the network dissolution of the silica which leads to the formation of $Si(OH)_4$ ions. Additionally, other products such as oligomers of the form $Si_nO_a(OH)_b$, where 2a+b=4n can also be produced. Consequently, at high pH, the $Si(OH)_4$ ions undergo ionisation and are converted to highly soluble ions. The dominant species of silica which are formed from this process are $H_3SiO_4^-$ and $H_2SiO^{2-}$. It was further reported that polymeric silicates may also be present. It is also important to note that ion exchange reactions generally occur as a means of decreasing the pH of the pore solution. As such, ions such as $Na^+$ may be bound in the reaction products. However, some of the alkalis in the gel may be replaced by $Ca^{2+}$ ions in a process called alkalis recycling whereby the result causes an increase in pH.

#### 2.3.2.2 Formation and gelation of colloidal silica

Ceteris paribus, to avoid supersaturation of aqueous silica and in the absence of calcium, the dissolved species will remain in the solution as their negative charges causes repulsion. However, in the pore solution of concrete, there is a considerable amount of $Ca^{2+}$ ions from the hydration process and other metal ions such as $Al^{3+}$ ions. These ions can undergo condensation reaction with the dissolved silica species to form poly-metal-silicates. The aggregation of the latter eventually leads to the formation of the ASR gel shown in Figure 2-3 (Rajabipour et al. 2015).

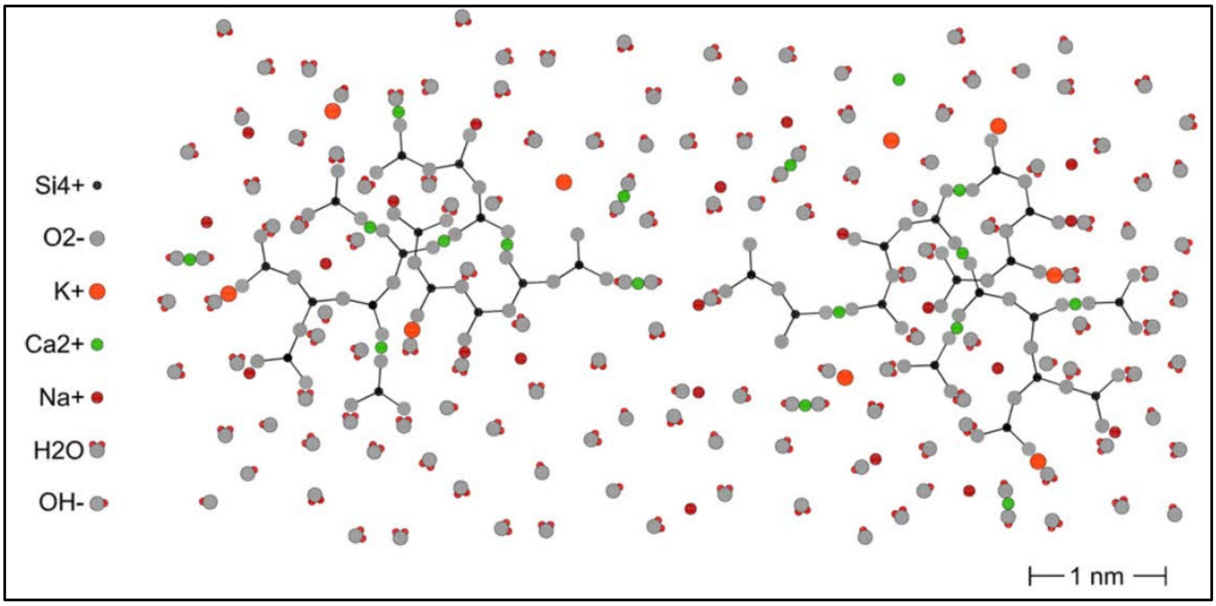

*Figure 2-3: ASR gel formed from clustering of colloidal silica particles* (Rajabipour et al. 2015)

Due to alkali diffusion into the swollen aggregate, a non-swelling C-N-(K)-S-H gel, which can be seen as CSH containing some alkali, is formed. The calcium content depends on the solubility of calcium hydroxide which is inversely proportional to the alkali concentration. It is further proposed by Helmuth and Stark that if CaO contribute to 53% or more of the C-N(K)-S-H gel on an anhydrous weight basis to the gel, only a non-swelling gel would form. Consequently, at high pH, whereby the solubility of calcium is decreased, a swelling N(K)-S-H gel is formed. However, the swelling gel in itself has a low viscosity and could easily diffuse away from the aggregate. The issue of ASR gel swelling arises where the two gels described above interact with each other to form a composite gel. The latter has an increased viscosity and decreased porosity, both of which increase the liability of expansion (Blight & Alexander 2011).

#### 2.3.2.3 Swelling of the gel

There are numerous possibilities as to how swelling of the gel may be induced. Primarily, the ASR gel has a high surface area which bears different hydrophilic groups such as -OH, -O or Na amongst other. These groups promote the absorption of water particles while osmotic gradients between the gel and the pore solution also favours the process (Alexander & Mindess 2005). Rajabipour et al (2015) presented findings from several authors about the swelling gel. These include the fact that the gel may be subjected to the Gibbs Donnan effect whereby the gel acts as a semi-permeable membrane which only allows movement of small particles. This implied that the gel becomes more saturated as small particles such as alkali ions penetrate the gel but larger ones such as the silica ions are unable to move out. Additionally, it was reported that the higher the concentration of Ca in the gel, the lower the swelling would be as the former increases the stiffness of the gel due to cross-linking.

### 2.3.3 Factors affecting ASR

It is well known that the three main requirements for the ASR process are a source of alkali, a source of reactive silica in the aggregate and sufficient moisture. All three of these conditions need to be fulfilled for the reaction to enter the stage whereby ASR damage can occur in concrete elements.

#### 2.3.3.1 Alkalis

It has been reported that a minimum concentration of 0.2 to 0.25M of hydroxyl ions is required to induce significant and sustained degradation of the silica. These can be derived from different sources in concrete.

##### 2.3.3.1.1 Alkalis from cement

The primary source of alkalis in the pore solution is the cement or binder which contain alkalis such as $Na_2So_4$ and $K_2SO_4$. Cement alkalis are quantified by their oxide values in particular by the amount of equivalent sodium oxide ($Na_2O$ eq) expressed as a percentage by mass of the cement as shown in Equation 2.

$$\%\, Na_2Oeq = \%\, Na_2O + 0.658\ \%\, K_2O \quad \textit{Equation 2}$$

The 0.658 is a constant used to convert the atomic mass of $K_2O$ in terms of the atomic mass of $Na_2O$. The sodium oxide equivalent is also used to categorise the cement. For instance, if this ratio is higher than 0.6, the cement is referred to as a high-alkali cement. Moreover, it is also used to calculate the amount of active alkali in the cement which is used, during the mix design process, to find out the maximum allowable amount of cement per cubic metre of concrete depending on the reactivity of the aggregates and other reactive components. From a local perspective, it was found that since 1998, the alkali content of locally produced cements have generally been in the range of 0.6% to 0.8% which classifies them as high-alkali cements (Oberholster 2009).

Additionally, during the cement hydration process, $Ca(OH)_2$ is also produced and consequently contribute to the available alkalis. However, in high alkali cements, the concentration of $Ca^{2+}$ is deemed to be low relative to the respective concentrations of $Na^+$ and $K^+$ ions. However, it is to be noted that not all the alkalis present in the concrete is available for the reaction processes. The fraction of available alkalis differs from cement to cement. This fraction is generally about 80 % of the total $Na_2O$ eq in south African CEM-1 cement. Eventually, the presence of these alkalis in the pore solution eventually lead to an increased pH which is generally in the range of 13 to 14.

#### 2.3.3.1.2 Alkalis from SCMs

Partial replacement of cement with SCMs is known to be an ASR mitigation measure. This is due to the fact that the amount of releasable alkalis from most SCMs are generally lower than that of the binder which is being replaced. However, it is to be noted that certain extenders such as high-Ca fly ashes contain relatively significant amount of alkalis. These could reach values of $Na_2O$ eq of up to or greater than 6%. In these specific cases, the SCMs were found to exhibit ASR mitigation properties only over a certain period of time which is usually around 10 years. Beyond this point, the reaction was found to start again which would consequently compromise the service life of the structure. As such, it is essential to be able to quantify the amount of releasable alkalis from SCMs. Several standards, such as the ASTM C311, have been derived for this purpose. However, none of the current tests methods which are commonly employed are able to quantify the amount of releasable alkalis over the design life of a structure and some concrete which were deemed to have sufficient amount of SCMs have exhibited ASR over the long term (Rajabipour et al. 2015).

#### 2.3.3.1.3 Alkalis from aggregates

Aggregates used in concrete mixes can also contain alkalis. As described in Section 2.3.2.1, it was found that silica in reactive aggregates undergo dissolution. In some aggregates, these silica structures may contain confined alkalis such as sodium. As the silica dissolves due to hydroxyl attacks, these alkali ions get released in the pore solution. For instance, it was found that soda-lime aggregates release sodium ions in the pore solution as it dissolves and consequently contribute to maintaining a high alkali level in the concrete. The phenomenon of alkali release from aggregates is also found in non-reactive aggregates. Alkalis from minerals, such as feldspar or clay minerals, in the non-reactive aggregates have been found to release alkalis into the pore solution. In some cases, the amount of these released alkalis was even found to be significant enough to affect the concrete prism test. The process via which these mineral phases release alkalis is still not completely understood but is thought to be mainly due to ion exchange reactions. Consequently, it is important to determine the amount of releasable alkalis from aggregates. This can be done by allowing the aggregates to leach out aggregates in distilled water or an alkaline solution. Currently several researchers in the TC 219-ACS committee at RILEM are working on deriving a test method to accurately portray this phenomenon (Rajabipour et al. 2015).

###### 2.3.3.1.4 Alkalis from other sources

Concrete mixes nowadays are very complex and it has become very common that chemical admixtures would be added to the mix to alter certain properties. For instance, superplasticisers are used to increase the workability of concrete. However, it is important to note that these admixtures may contain alkalis. These need to be included in the alkali content of the concrete mix as depending on the amount of admixture used, the contributing alkalis level may be significant enough to induce ASR. Additionally, in cold climate countries, de-icing and anti-icing chemicals are often used. These may comprise of NaCl, alkali acetates and alkali formates which are all possible sources of alkalis. Lastly but not least, the environment surrounding the concrete element may also act as a source of alkalis. For instance, in structures exposed to the sea such as a pier, alkalis may diffuse from the seawater to the concrete pore solution (Oberholster 2009).

#### 2.3.3.2 Aggregates

The aggregates in the concrete are the site at which ASR occurs. At present, the practical solution is to quantify the reactivity of the aggregates based on standardised tests and adjust the concrete mix design accordingly. However, it has been found that not only the reactivity of aggregates is important when considering ASR potential. As such, understanding the composition and behaviour of aggregates is of utmost importance in dealing with ASR.

###### 2.3.3.2.1 Aggregate type

For an aggregate to exhibit deleterious ASR expansion, the former must have a source of reactive silica and must be dense. In the case of the second condition, if the aggregate is porous, the gels will simply fill the voids present in the aggregates and therefore may undergo less expansion relative to a denser aggregate for the same amount of gel produced. The first condition that is the source of reactive silica is usually more significant in commonly used aggregates. As the amount of reactive silica increases, the amount of expansion is expected to increase. Moreover, the mineralogy of the reactive silica is also important in terms of ASR potential. It was found that the thermodynamic stability of silica deteriorates as the degree of microstructural disorder increases. This implies that amorphous silica such as opal would experience more ASR expansion than the same amount of crystalline silica such as cristobalite (Oberholster 2009).

###### 2.3.3.2.2 Reactive aggregate content

Over the years, studies on ASR have been conducted in different countries using a variety of different aggregates. In certain cases, it has been found that some of the aggregates containing highly-reactive forms of silica exhibit a pessimum effect. The terminology of pessimum of defined by contrast to the word of optimum. In simple terms, it implies that there exists a certain amount of reactive aggregate, defined as the pessimum ratio, at which the reaction is maximum. If the amount of reactive aggregates is decreased or increased from that point, the amount of ASR expansion would decrease as described in Figure 2-4 (Binal 2015).

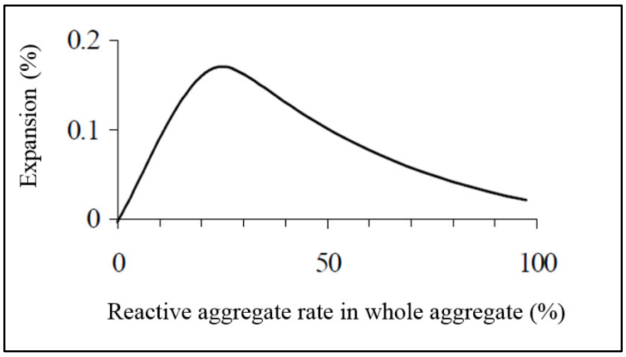

*Figure 2-4: Typical graph of the pessimum effect* (Binal 2015)

The pessimum content varies with varying levels of alkalis in the pore solution. Above the pessimum amount, it is believed that there is an excess of reactive silica which consumes the free alkalis before hardening of concrete occurs. As a result, the expansion is diminished from that point. Moreover, several authors have even suggested that the pessimum will generally occur when the reactive silica to available alkalis ratio 6. Even though, the phenomenon of pessimum ratio is well-understood, standardised accelerated tests do not usually take this property into consideration as specific proportions of aggregates to cement by weight are generally specified. As shown in Figure 2, the pessimum content may be significant enough to classify an aggregate as deleteriously reactive or slowly reactive and as such should be incorporated in the development of accelerated tests in the future (Rajabipour et al. 2015).

#### 2.3.3.2.3 Aggregate size

Based on the application or structural element, different nominal aggregate sizes are used in the construction industry. It was expected that less ASR expansion would occur if the size of aggregate used is increased as a result of the decrease in surface area. However, several studies carried out have shown that this is not always representative as the maximum ASR expansion due to an aggregate may occur at an intermediate particle size, referred to as the pessimum grain size, and does not vary monolithically with aggregate size. For instance, Gao et al (2013), showed that the ASR expansion of siliceous limestone was maximum with aggregate size in the range of 315-630 μm as shown in Figure 2-5 (Gao et al. 2013).

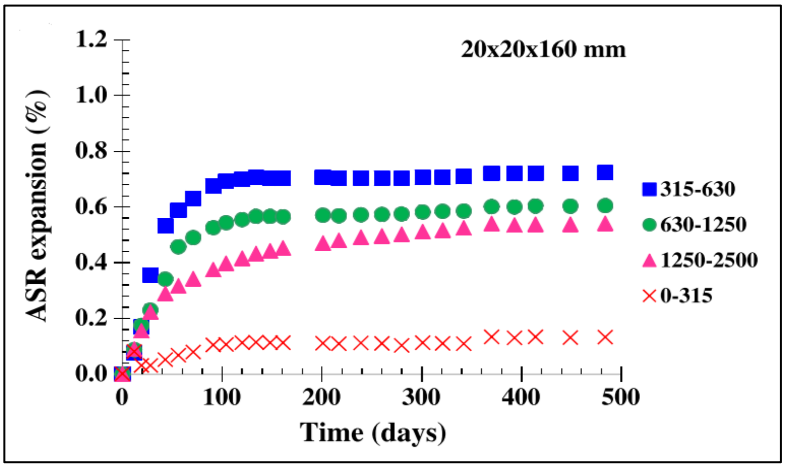

*Figure 2-5: Pessimum grain size* (Gao et al. 2013)
**Note: values in legend refer to grain size ranges in μm*

Several hypotheses have since been suggested to explain the pessimum grain size effect. It has been proposed that the very fine reactive aggregates may mitigate ASR expansion through pozzolanic action. However, this does not hold true whereby the pessimum grain size is higher. Another hypothesis amongst others is that related to the contact between the reactive silica and the hydroxyl ions. It is proposed that in large particle sizes the hydroxyl ions have to migrate inside the aggregates to reach the reactive silica while for smaller particle sizes this distance may be reduced and the reactive silica may be more easily accessible. Due to this dependency on aggregate size, it becomes necessary that an aggregate is tested at the size in which it would be used in the construction process. This further implies that the standardised tests whereby graded aggregate sizes are specified may not be adequate to determine ASR potential of a certain aggregate (Rajabipour et al. 2015).

#### 2.3.3.2.4 Surface vs intra-particle reaction

The location of the reactive silica also plays a role in the determination of alkali silica reaction potential of an aggregate. For aggregates of uniform composition such as volcanic or synthetic glasses, the reaction will readily occur at any contact point of the aggregate with the pore solution and will usually be on the surface as shown in Figure 2-6a. However, most aggregates used in concrete are heterogeneous in composition, that is, the reactive silica is not necessarily present at the surface of the particles. An example of which would be greywacke whereby the reactive silica is confined in a non-reactive matrix. Consequently, the reaction may be slower, depending on the porosity of the matrix, in such aggregates as the pore solution has to diffuse into the aggregate to reach the silica. Another result of this process is that the gel would normally form inside the aggregates or in cracks in the aggregates as shown in Figure 2-6b (Rajabipour et al. 2015).

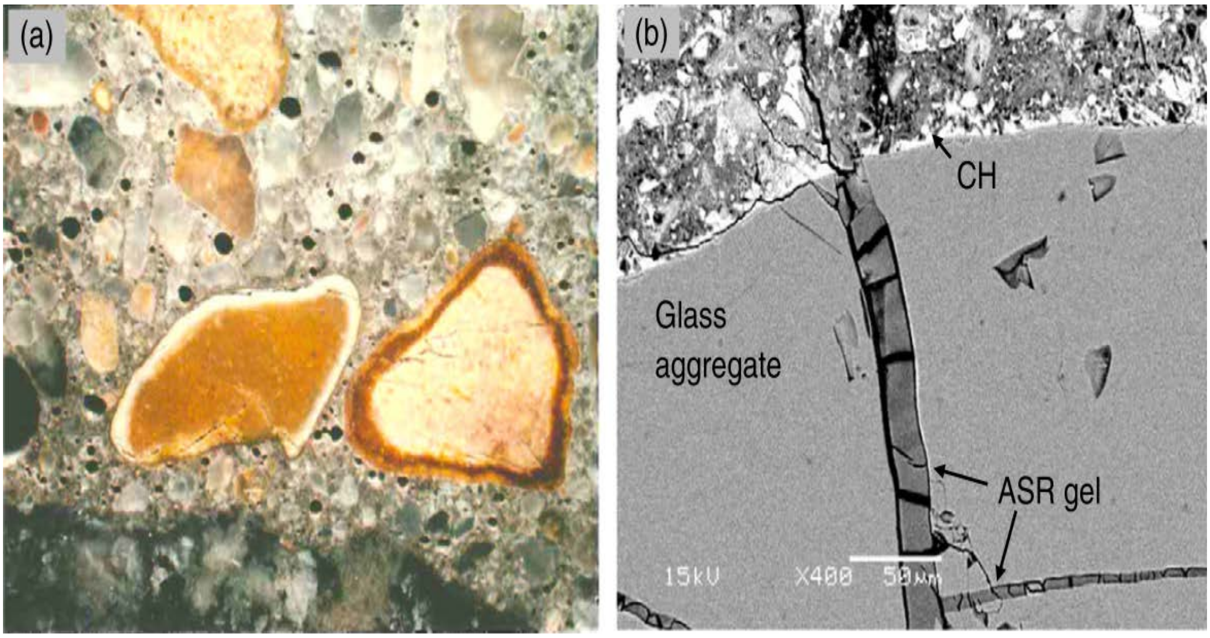

*Figure 2-6: (a) ASR on the surface of a granite gneiss particle (b) ASR in microcracks in a soda-lime glass particle* (Rajabipour et al. 2015)

#### 2.3.3.3 Exposure conditions

The conditions to which the concrete is exposed to such as moisture level and temperature play a significant role in ASR expansion. It is well known that hydroxyl ions are required to start the chain reaction leading to ASR. As such, it can be expected that structures in regions with higher relative humidity or rainfall recurrence would be more prone to undergo ASR expansion. However, certain structures in very dry areas have also been diagnosed over the past. An explanation to this phenomenon would be that the internal moisture levels of these structures were sufficient to promote expansive ASR. Research has shown that in general, an internal humidity of 75-85% is enough in this regard. This value however is only valid at room temperature as Poyet et al. (2016) has shown that ASR expansions may still occur at 59% RH when the temperature was increased to 60℃. It is further suggested by Oberholster (2009) that the rate of expansion under field conditions is expected to double when the temperature is increased by 10℃.

### 2.3.4 ASR mitigation measures of new concrete

Over the years, several methods such as external strengthening have been developed to remedy to ASR damaged structures in the view to restore structural stability. However, the ideal situation would be to prevent ASR from occurring in the first place. This can only be accomplished by taking ASR into consideration at the design stage of the concrete mix and apply mitigation measures if necessary. As described in Section 2.3, there are three main factors, namely a source of alkali, a source of reactive silica and sufficient moisture levels, essential for the reaction to occur. Any method of removing one of the factors would consequently prevent ASR. This section provides mitigation measures which could be employed for this purpose.

#### 2.3.4.1 Use of low-alkali cement

It was previously stated that the reaction there is a minimum alkali content which is required to start the reaction and sustain expansive gel formation. This value is thought to be approximately around 0.6 $Na_2O$ eq. Alternatively, some standards also express their prescribed limiting value in terms of kilograms per cubic metre. In that context, the AASHTO-PP65 advises that a cement of alkali content less than 1.8 kg/m$^3$ should be use for structures with moderate risk of ASR (Rajabipour et al. 2015). As such, using a cement with an alkali content lower than this value would generally be sufficient to prevent the reaction from occurring. The major issue with this solution is that not all countries have access to low alkali resources to produce low-alkali clinker. Currently, in the Western Cape, the alkali content of CEM II A-L 52.5N is approximately 0.8 $Na_2O$ eq which is considerably higher than the limit.

#### 2.3.4.2 Use of SCMs

Research on the use of extenders with the aim of mitigating ASR has been carried out for a long time. The pioneering work of Stanton in 1950s demonstrated that supplementary cementitious materials such as fly ash or slag were effective in doing so. Since then, many studies have been performed on SCMs use mainly to explain the mechanisms behind which these extenders work and to optimise the blending ratios of the binder.

#### 2.3.4.2.1 Mechanism of ASR mitigation by SCMs

It has been found that there are different mechanisms via which cement extenders can help diminish the formation of the expansive ASR gel. Initially, it was proposed that the partial substitution of cement from the mix results in a decrease in alkalis as the cement extenders generally tend to have a lesser amount of releasable alkalis even though that they may have a higher total alkalis content. This phenomenon has been termed the dilution effect. However, several studies have shown that this reaction cannot be entirely responsible for the amount of reduction experienced in expansion. Therefore, the idea of a reaction effect whereby the SCMs react with the alkalis in the pore solution was put forward. Since then, this phenomenon has been delved into further and a better understanding of the reaction process is now available (Oberholster 2009).

Alkalis released from the hydration process can be present in concrete in three ways namely dissolved in the pore solution, bound in hydration products or as a constituent of the ASR gel. Several studies have shown that SCMs reduce ASR expansion by diminishing the concentration of alkali hydroxides in the pore solution. Some of the extenders used in construction use the alkali hydroxide in their reaction. For instance, fly ash uses up calcium hydroxide in its pozzolanic reaction. In this regard, it was found that silica fume is the most efficient extender in the short term as its use results in a more significant decrease in $OH^-$ concentration as shown in Figure 2-7 (Thomas 2011).

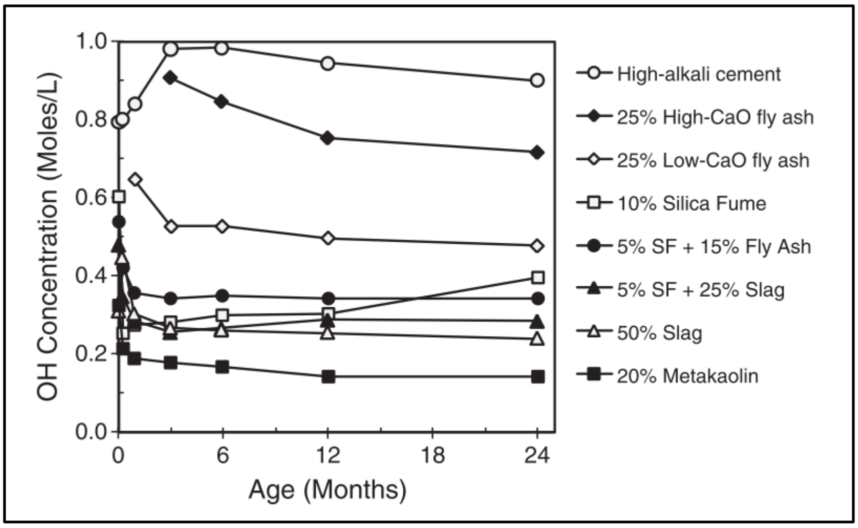

*Figure 2-7: $OH^-$ concentration over time wrt extender replacement levels*(Thomas 2011)

Over a longer period, approximately 3 months, it was found that the $OH^-$ concentration in the pore solution of mixes containing silica fume starts to increase again. However, this phenomenon was found only mixes containing silica fume as the other mixes involved in the study did not show any sign of increasing hydroxide concentrations. Consequently, it was deduced that alumina which is present in fly ash and slag may also play a role in the alkali binding properties of the extenders (Thomas 2011). Gholizadeh et al. (2016) later confirmed this hypothesis in their study whereby it was found that $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ markedly increase the alkali binding capacity of extenders. The same study showed that increasing concentrations of CaO, MgO or $SO_3$ promote ASR expansion. The opinion that CaO affect ASR is mirrored in the review paper written by Thomas whereby the findings of several studies were detailed. It was put forward that the alkali absorption capacity of extenders is affected by the Ca/Si ratio. When the calcium content is high, the charge on the C-S-H particle is positive and therefore repels the cations. However, when the ratio of Ca/Si is low, the charge becomes negative and the calcium silica hydrates product are able to absorb the cations found in the pore solution.

#### 2.3.4.2.2 Dosage levels of SCMs

SCMs are nowadays one of the most commonly means employed to mitigate ASR expansion. Several standards even propose minimum replacement levels at which these extenders should be used. In South Africa (Western Cape), fly ash and GGBS are the two main extenders used for this purpose and minimum replacement levels of 20% FA by mass or 40% S by mass, of the total binder content, are advised in SANS 1491. However, it should be noted that the amount of extenders to be used should be accurately calculated in construction as these replacement levels depend on several factors such as alkali contribution from the cement and reactivity of the aggregates amongst others as shown in Figure 2-8. For instance, 20% fly ash may be sufficient to mitigate ASR in a concrete containing granite aggregate but may still be insufficient if a more reactive aggregate such as greywacke is used (Thomas 2011).

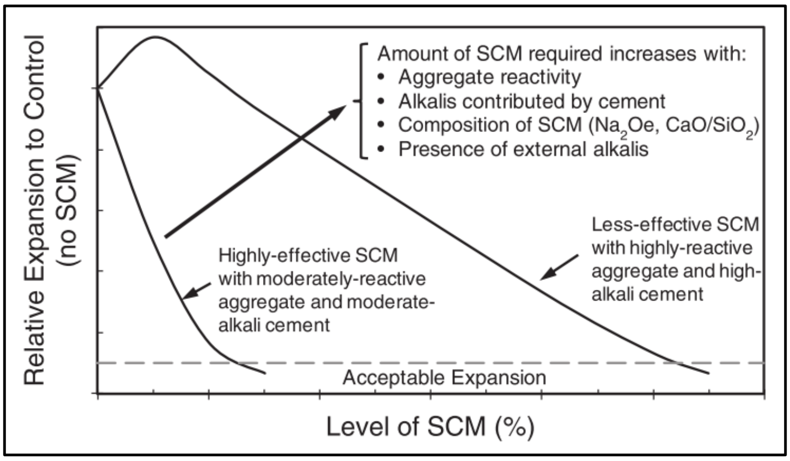

*Figure 2-8: Conceptual relationship of expansion versus SCMs level* (Thomas 2011)

### 2.3.4.3 Use of chemical admixtures

Chemical admixtures can also be incorporated in the concrete mix to reduce ASR gel formation. Oberholster (2009) reported that it was established in 1951 that lithium-containing compounds are the most effective admixtures in controlling ASR. Furthermore, it was added that lithium nitrate and lithium hydroxide monohydrate are the two most promising compounds in this regard. Since then several studies have been dedicated to identifying the mechanisms by which these compounds react and a few have been proposed. It has been suggested that a protective barrier constituting of silicon and lithium may form on the surface of silica grains and therefore prevents the ingress of sodium and potassium ions. Other researchers proposed that the lithium ions contribute to an increased stability of the silica and a more stable and rigid gel is formed. Finally, it has also been reported that the lithium ions cause an increase in solubility of the silica which consequently remain in the solution and therefore prevent the formation of gels. Even though the exact mechanisms are still not fully understood, the use of lithium compounds remain one of the most significant ASR mitigation measures. However, due to the fact that the lithium compounds behave differently with different aggregates and that their cost is higher with respect to other ASR mitigation measures, they are not commonly used in the construction industry (Owsiak 2016).

#### 2.3.4.4 Use of non-reactive aggregates

As previously mentioned, reactive silica from aggregates is one of the essential components of ASR processes. However, the extent of expansion depends on the reactivity of the aggregates in terms of ASR. Several standardised tests such as the concrete prism test or the accelerated mortar bar test have been used to characterise this reactivity. As such, it can be determined whether an aggregate would be more prone to ASR than another one based on the expansion achieved through these tests. Consequently, if available in the industry, non-reactive aggregates could be used instead of reactive ones in the concrete mix (Rajabipour et al. 2015).

### 2.3.5 Test methods to evaluate ASR potential

Since the discovery of alkali silica reaction, several test methods have been derived to assess the ASR potential of aggregates, cements and/or cement extenders. These tests can be classified into three main categories namely:

- Preliminary screening test;
- Indicator tests; and
- Performance test.

#### 2.3.5.1 Preliminary screening test

The preliminary test methods do not provide quantitative results and are mainly used to make an interim assessment of aggregates. The petrographic examination is a type of preliminary test used to classify aggregates based on their mineralogical composition. The test evaluates the amount of siliceous and carbonate materials present in the aggregates with the aim of evaluating whether these would be prone to ASR. The test can only be performed by a professional petrographer as knowledge in mineralogy is required. The gel-pat test is another preliminary screening test. The aggregate in fine fractions is embedded in a cement pat and stored in an alkaline solution at 20℃ or 80℃. Examination for signs of ASR gel and reaction is done after 10 days (Blight & Alexander 2011).

#### 2.3.5.2 Indicator tests

Indicator tests are used to provide a first sign on the potential of alkali aggregate reaction. Since these tests are relatively short compared to performance tests, they are commonly used in the construction industry, and many different tests as well as varying versions of the same test are available. This section puts forward the most commonly used indicator tests.

Firstly, there is the chemical method presented in ASTM C289-07. The test covers the chemical determination of the potential reactivity of an aggregate with alkalis in Portland-cement concrete as indicated by the amount of reaction at 24 hours. The aggregates are graded and only materials passing a 300 μm sieve and retained on a 150 μm sieve are used in the procedure. Moreover, the specimens are conditioned at 80°C in a 1N sodium hydroxide solution. Nevertheless, due to the unreliability of this test, this method is mainly employed as a first indicator and other tests are usually used to confirm the findings. It is also to be noted that this test has been withdrawn without replacement from the standard in 2016.

Secondly, there is the mortar bar test (MBT) illustrated in ASTM C227-10. This method determines the susceptibility of cement-aggregate combinations to expansive reactions with alkalis. The extent of the reaction is determined through the measurement in length of the mortar bars (25×25×285 mm). Pertaining to the concrete mix, a specific grading of the size fractions of the aggregates is specified in the standard. It is also specified that the cement, which is to be used in the mix, should be the closest representative of the job cement, and in the situation where a combination of cement types is to be used, the cement which has the highest alkali content should be used. In terms of proportioning, it is specified that the aggregate should be 2.25 times the mass of cement. After demoulding, a first measurement is taken and subsequently, the specimens are stored on end over, but not in contact with, water in a storage container at 38° C. A second reading is taken at 16 days from moulding and the difference in length is used to quantify the alkali reactivity of the specimens. Nevertheless, it is highly recommended to take measurements over a prolonged period which may extend to six months.

Finally, there is the accelerated mortar bar test (AMBT) which is the most commonly used indicator test based on the South African NBRI accelerated test method. Due to its popularity, there are several versions of the AMBT of which the most well-known are AAR-2 (RILEM), ASTM C1260-14, ASTM C1567-13 (SANS 6155 equivalent) and SANS 6245:2006. The AMBT follows the general principle of the mortar bar test explained above. The reactivity of the constituents is again determined through measurement of the length change of the mortar bars (25×25×285 mm) with the same proportioning process. However, in this test the specimens are totally immersed for 24 hours after demoulding in distilled water at 80°C. After that period, a zero reading is taken and the specimens are then submerged in a 1M NaOH solution at 80°C. Readings are subsequently taken at regular intervals (usually 3-day intervals) before a final reading is taken at 14 days after immersion in the NaOH solution. Measurements are usually taken over an extended period after the final reading in experimental scenarios.

However, the different versions of the test differ slightly from each other. Firstly, the ASTM C1260 and SANS 6245 methods explicitly specify that a cement with low alkali (assumed $Na_2O_{eq} \leq 0.6\%$) should be used, while the AAR-2 method specifies the use of a cement with minimum $Na_2O_{eq}$ of 1.0%. ASTM C1567 allows the use of job cements and blended cements. Moreover, the AAR 2 has two further variants of its own which are AAR-2.1 which specifies the use of a 25×25×285 mm mould while AAR-2.2 specifies the use of a 40×40×160 mm mould.

#### 2.3.5.3 Performance test

The most reliable of all the performance tests is the field performance test, also referred to as structural monitoring, when actual 'simulated' or real structures are used in the testing. In this method, the specimens/structure is cast using the job mix and left exposed to the prevailing environmental conditions. Strain targets are placed on the specimens and readings are taken at regular intervals. In these conditions, reliable results are only expected at an age of 2 years minimum and testing generally spans for several more years.

Secondly, there is the concrete prism test (CPT) which is described in ASTM C1293-08b and AAR-3 (RILEM). The test covers the determination of the alkali aggregate reaction potential of concrete prisms (75×75×250 mm) through the measurement of expansion. Both test methods specify the use of a cement which has a $Na_2O_{eq}$ of approximately 0.9%. Standard practice is to boost the alkali content (i.e. the $Na_2O_{eq}$) to 1.25% using sodium hydroxide. Pertaining to aggregate grading, both test methods provide a general gradation of the size fractions to promote stability of the mix. However, in the case of ASTM C1293-08b, the grading is specified only for the coarse aggregates. On the other hand, the AAR-3 method specifies the grading of both fine and coarse components of the aggregates as well as specifying a ratio of coarse/fine aggregates of 60/40. Both methods include casting the specimens, demoulding them after 24 hours and taking a zero reading, and storing them on end over, but not in contact with, water in storage containers at 38°C. Subsequently, readings are taken at regular intervals which vary slightly for the two methods. In general, if only Portland cement is present, the test is run over a period of 1 year, while the addition of supplementary cementitious materials prolongs the test to 2 years. Finally, the most noticeable difference between the two methods can be seen in the expansion limits specified. The ASTM C1293-08b method specifies that a specimen should be classified as deleteriously reactive when the expansion after the testing period is greater than 0.04%. On the other hand, the AAR-3 method is more flexible and provides a range of 0.03% to 0.05% depending on the reactivity of the aggregates used in the mix. In a recent study, the 'EU PARTNER PROJECT'(Lindgård et al. 2010), it was found that those two types of tests are prone to alkali leaching due to the small cross-sectional area of the specimens. The 'Norwegian CPT test'(Lindgård et al. 2010) which follows the same principle as the ASTM C1293 fares better in this regard as it makes use of larger prisms with cross section 100x100 mm.

Lastly, there is the accelerated concrete prism test (ACPT) described in AAR-4.1 (RILEM). The method follows the same principle as the concrete prism test from AAR-3 (RILEM), but lasts for a shorter period (usually 20 weeks) due to the exposure conditions. The specimens are stored at 60°C, instead of the conventional 38°C, which boosts the reaction process and therefore allows for earlier determination of alkali aggregate reaction potential.

## 2.4 Summary of literature review

The literature reviewed in this chapter can be summarised in the following points:

- There are three main types of alkali aggregate reaction, AAR, based on the type of aggregate which is used. In the local context of the Western Cape, the use of greywacke and granite aggregates entails that alkali silica reaction, ASR, would be the primary concern;
- The visible characteristics of ASR include the presence of whitish product, gel, cracks through aggregates and matrix and voids filled with reaction products;
- ASR is a consequence of a sequence of reactions which include the dissolution of metastable silica, the formation of nano-colloidal silica sol, the gelation of the latter and swelling of the gel;
- Two types of gels, a swelling and a non-swelling gel can be formed from the ASR reaction depending on the proportion of calcium ions in the reaction products. However, it is a combination of both gels which generally result in a composite expansive gel;
- There are three main factors necessary for the reaction to take place namely a sufficient source of alkali, a source of reactive silica and sufficient moisture levels;
- The alkali content of cements is measured in terms of sodium equivalent ($Na_2O$ eq) and a value of greater than 0.6 entails that the cement is classified as a high-alkali cement and would be more prone to ASR;
- The main source of alkalis is the cement, but other sources may include the cement extenders, aggregates or admixtures which are used in the concrete mix. It is important to consider the alkali from these secondary sources in the calculation of the total alkali content of the concrete mix;
- The aggregate type is also a determining factor in the extent of ASR expansion. It was found that amorphous silica is more readily reactive than crystalline silica;
- There exist pessimum values with regards to the amount of aggregate and aggregate grain size whereby the reaction is maximum for certain aggregates. Below or above the pessimum value the extent of reaction consequently decreases;
- The reactivity of certain aggregates may vary as they might have a non-reactive matrix and a reactive silica in the core of the particles. In these cases, the porosity of the matrix and the presence of cracks would determine the rate at which the reaction would proceed;
- The moisture level should generally be in the range of 75-85% for sustained expansive gel formation. It is to be noted that in large structures, the internal moisture of the element may fulfil this requirement;
- Low alkali cement that is with a sodium equivalent of less than 0.6 should be used if no other mitigation measures are employed when using highly reactive aggregates;
- Cement extenders have been found to decrease ASR expansion through the dilution and reaction effects. The first entails substituting cement with an extender that has a lower

level of releasable alkalis. The second entails the exhaustion of alkali hydroxides in the pore solution and alkali binding capacity.

- The alkali binding capacity is increased through a reduction of CaO, MgO or $SO_3$ or an increase in $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ content in the extenders;
- The dosage levels of cement extenders should be calculated precisely as they depend on several factors such as reactivity of aggregates or amount of releasable alkalis of the cement;
- Although costly, lithium compounds, especially lithium nitrate and lithium hydroxide monohydrate, are very effective with ASR mitigation. However, care should be taken about the type of aggregate which is being dealt with as the compound is not universally compatible with all aggregates;
- The use of non-reactive aggregates should be encouraged if available.
- There are three different test classes used to determine the SAR potential of aggregates namely preliminary screening test, indicator test and performance tests. Performance tests are the more reliable option;
- Indicator tests are generally the most commonly used testing method for ASR due to their relative short period of testing with respect to performance tests; and
- Some of the indicator tests especially the accelerated tests do not fully depict the actual situation due to aggregate gradation, aggregate content or cement type and cement content specifications associated with the standardised tests and as such should be used only as indication tests.

# 3 Experimental methodology

## 3.1 Overview of chapter 3

This chapter will make use of the information collected from the literature review to design the experimental procedures required to evaluate the potential of ASR in the experimental mixes. A detailed flow chart of the process is given below.

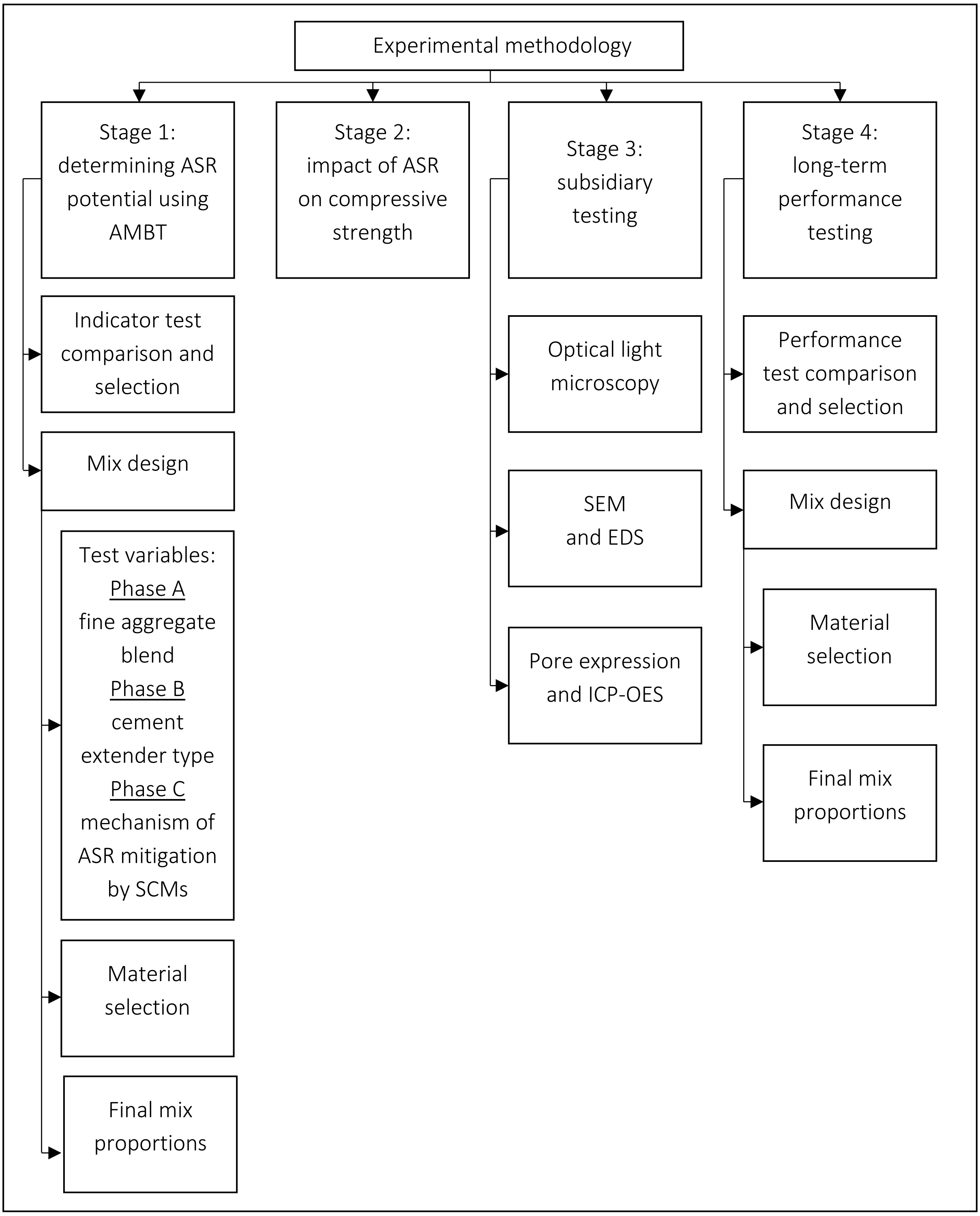

*Figure 3-1: Experimental technique overview*

The chapter is subdivided into four main stages of testing, which were performed in chronological order. The first stage of testing is further subdivided into 3 phases. Phase A depicts the use of an accelerated mortar bar test with the aim of determining a measure of the expansion which is to be expected from the use of reactive fine aggregate in conjunction with reactive coarse aggregate in 'micro-concrete' mixes, at least on a comparative basis. The effect of using cement extenders as a means of mitigating ASR expansion was then investigated in Phase B. Phase C of Stage 1 makes use of a nominally 'inert' limestone filler as substitute for the cement extenders with the aim of identifying the different mechanisms involved in the ASR reaction. The second stage looked at investigating the impact of ASR gel formation on one of the most important concrete mechanical properties, which is its compressive strength. Subsidiary testing namely; microscopical analysis, energy dispersive spectroscopy and pore solution analysis, were then investigated in Stage 3 to complement the results of the first two stages. Finally, the fourth stage involved the preliminary testing of 'real-life' concrete mixes for ASR using long-term testing methods.

## 3.2 Stage 1: determining ASR potential using AMBT

The first stage of testing was dedicated mainly to identifying the extent of ASR expansion in the different concrete mixes. The latter were designed based on the three main objectives set in the first chapter, viz: identifying the effect of using greywacke as crusher in the mixes, using SCMs to mitigate any excessive expansion and understanding the mechanisms of ASR mitigation by using the cement extenders and will be discussed further in Section 3.2.3. The first step in this process was however to choose a test method which could be used to quantify ASR expansion. An AMBT test, more specifically a modified version of the RILEM AAR-2 test, was eventually chosen.

### 3.2.1 Indicator test comparison and selection

The aim of this research is to identify the alkali aggregate reaction potential of concrete mixes, or suitable proxies for these mixes, which are currently being used in the Western Cape. As such, the tests which are to be chosen should allow the use of a job concrete mix. Moreover, due to the limited time allocated for the completion of this research, the tests should be short enough to allow for comparison of a range of concrete mixes over the period of study. Table 3-1 provides a comparison of the indicator tests based on the criteria given in the table. Also, under the table is a qualitative evaluation of the tests in terms of desirable characteristics.

As can be seen from Table 3-1, five factors namely; cement type, aggregate grading, mould size, testing period and temperature, have been selected to determine which of the tests is more suited for this study. One of the aims of this research is to mimic job mixes as closely as possible. In this context, it was identified that ASTM C227-10 and ASTM 1567-13 allow for the use of the job cement. Additionally, ASTM C227-10 is performed at a temperature of only 38 ° C which is closer to normal temperatures than the 80 $^{o}$C of the other tests. Nevertheless, the lower temperature means that the test needs to be carried for a longer period which could significantly limit the number of mixes tested. Pertaining to the aggregates, all the tests required a specific grading of aggregates which are all almost identical, minor discrepancies being in the nominal sizes of the sieves. However, all the sizes specified are in the range of fine aggregates, and the standardised tests completely disregard the use of a coarser aggregate fraction. Since the aim of this research was to mimic 'real-life' concrete mixes it was decided that the test chosen must be modified to allow for the use of a coarser fraction. In this regard, RILEM AAR-2 would be more suitable as it provides the choice of a bigger mould size which can accommodate a 9.5mm coarse aggregate, effectively creating the possibility of achieving a 'micro-concrete'.

*Table 3-1: indicator test comparison*

| Standard | ASTM C227-10 | ASTM 1260-14 | ASTM 1567-13 | SANS 6245 | RILEM AAR-2 |
|---|---|---|---|---|---|
| Cement type | Job cement | Low alkali cement | Job cement | Low alkali cement | High alkali |
| Aggregate grading | Graded | Graded | Graded | Graded | Graded |
| Mould size (mm) | 25×25×285 | 25×25×285 | 25×25×285 | 25×25×285 | 25×25×285or<br>40×40×160 |
| Testing period (days) | 16+ | 16 | 16 | 14 | 16 |
| Temperature (℃) | 38 | 80 | 80 | 80 | 80 |

| | | |
|---|---|---|
| 🟩 | 🟨 | 🟥 |
| → More desirable to least desirable (green to red) | | |

Based on the information and evaluation, it was found that the RILEM AAR-2 would be the most suitable test in this study. The dry materials were proportioned as 1 part cement to 2.25 parts of aggregates by weight. The water to binder ratio was kept constant at 0.47. Nevertheless, the following modifications were done to the standardised test so that it more closely resembled a job mix:

- A commercial job cement, being a CEM II A-L/52.5N with approximately 6-20% of ground limestone was used, instead of the high alkali cement (greater than 1.0 % $Na_2O_{eq}$) specified in the standard, and the total alkali content was boosted to the required amount using NaOH solution;
- The reactive fine aggregates were not to be graded, but instead would only be sieved for particles sizes between the range of 150 μm to 4750 μm to more closely resemble 'real-life' mixes;
- The material proportioning of the mixes was based on the standard test with the exception that 60% of the total aggregate content by mass would be made up of a 9.5mm coarse aggregate with the aim of creating a 'micro-concrete'; and
- The test was prolonged to 28 days as the effects of deviating from the norm were still unknown and additional information would be crucial in understanding the changes.

#### 3.2.1.1 Modified RILEM AAR-2 test procedure

The modifications mentioned above were implemented in the mix proportioning phase of the test. The testing procedure followed the same principle as the RILEM AAR-2 standard and is as listed:

- Three specimens of 40×40×160mm were cast for each mix;
- After 24 hours, the specimens were demoulded, marked and strain targets were placed on two opposite longitudinal faces;
- An initial target placement, $L_i$, reading to the nearest 0.001mm was taken;
- Specimens were immersed in distilled water and kept for 24 hours in an oven at 80±2˚C;
- After 24 hours, the specimens were removed one at a time, surfaces dried with a cloth and a zero reading, $L_0$, was taken to the nearest 0.001mm;
- The specimens were then placed in a 1M NaOH solution at 80±2˚C; and
- Subsequent expansion readings were taken at 1, 3, 6, 9, 14 and 28 days.

*Figure 3-2: AMBT test specimens (left), strain gauge (right)*

### 3.2.2 Mix design

#### 3.2.2.1 Test variables

A comparative approach was employed in the mix design using contrasting variables with the aim of identifying any trends which may arise from the use of specific materials in the concrete mixes. These variables were chosen based on the three main research questions which are being investigated in this study:

- Whether the use of greywacke crusher sand (which is known to be alkali reactive) has an impact on alkali-silica reaction potential of a concrete mix? If so, is there a 'critical amount' which results in maximum expansion?
- If yes, whether these effects can be minimised/reduced using common commercial cement extenders?

- Do those cement extenders contribute to the reduction in ASR expansion by simply diluting the overall cement content, or do they also contribute by way of further alkali reactions?

Since the research questions are inter-dependent, it was decided that this stage of testing should be further subdivided into three main phases to allow for a progressive mix design process.

#### 3.2.2.1.1 Phase A - fine aggregate blend

The first aim of this research was to identify the effect of using reactive aggregate, in the form of crusher sand, in conjunction with reactive coarse aggregate on the potential of alkali silica reaction in concrete mixes. To do so, 7 mixes were initially designed with varying levels of greywacke crusher sand. Mix A0 served as a control depicting the usual standard AAR-2 test, that is, it consisted only of reactive fine aggregate in the fractions specified in the RILEM AAR-2 standard. The subsequent six mixes contained 60% coarse aggregate and the remaining 40% was fine aggregate in the total aggregate blend. By varying the fine aggregate blend with several fractions of greywacke crusher sand and Philippi dune sand, the effect of greywacke crusher sand was investigated. The greywacke crusher sand was substituted into the mix in increments of 20% of the total sand blend.

Through the testing performed, it was found that a maximum expansion occurred in the range of 40-60% greywacke crusher sand. Consequently, it was decided to refine the testing in that range and a further 3 mixes were added to the testing regime with increments of 5% reactive crusher sand. Mix A3 and A7 were also repeated in the refinement stage. A descriptive list of the mixes tested in phase A of testing is provided in Table 3-2.

*Table 3-2: Phase A - Investigation of reactive crusher sand influence on ASR*

| Mix | Variable | |
|---|---|---|
| | Type | Description of sand blend |
| A0 (ref) | 0% coarse and 100% fine | 100% crusher sand; 0% Philippi dune sand |
| A1 | 60% coarse and 40% fine | 100% crusher sand; 0% Philippi dune sand |
| A2 | 60% coarse and 40% fine | 80% crusher sand; 20% Philippi dune sand |
| A3 | 60% coarse and 40% fine | 60% crusher sand; 40% Philippi dune sand |
| A4 | 60% coarse and 40% fine | 55% crusher sand; 45% Philippi dune sand |
| A5 | 60% coarse and 40% fine | 50% crusher sand; 50% Philippi dune sand |
| A6 | 60% coarse and 40% fine | 45% crusher sand; 55% Philippi dune sand |
| A7 | 60% coarse and 40% fine | 40% crusher sand; 60% Philippi dune sand |
| A8 | 60% coarse and 40% fine | 20% crusher sand; 80% Philippi dune sand |
| A9 | 60% coarse and 40% fine | 0% crusher sand; 100% Philippi dune sand |

#### 3.2.2.1.2 Phase B – cement extender type

The second aim of this research was to identify the effect of supplementary cementitious materials on the potential of alkali silica reaction. For these AMBT tests (AAR-2), mix A5 from phase A, described as mix B0 in this phase, was chosen based on its performance, as a basis for the mix design. Consequently, cement extenders were substituted in the binder blend at varying levels. Through the literature reviewed in Chapter 2, it was found that 20% fly ash and

40% corex slag are individually sufficient in mitigating the negative impact of ASR gel formation. As such, mixes B1 to B7 were designed to have varying extender proportions on either side of these limits. The mixes involved in this phase of testing are depicted in Table 3-3.

*Table 3-3: Phase B - Investigation of SCMs influence on ASR*

| Mix | Extender amount and type |
|---|---|
| B0 | 0 % extender |
| B1 | 40% GGCS |
| B2 | 50% GGCS |
| B3 | 60% GGCS |
| B4 | 20% fly ash |
| B5 | 30% fly ash |
| B6 | 40% fly ash |

#### 3.2.2.1.3 Phase C – mechanism of ASR mitigation by cement extenders

The third phase of stage 1 of the experiments revolved around the mechanisms by which cement extenders work to reduce ASR. As explained in Chapter 2, SCMs generally have a releasable alkali content lower than most common cements, and as such substituting cement for cement extenders effectively reduces the total alkali content available for the reaction. However, previous research (Shafaatian et al. 2013) also pointed out that the cement extenders may also bind free alkalis in the pore solution, further reducing ASR gel formation.

This phase attempted to discriminate between these two processes by simply substituting the cement extender with an inert filler and measuring the expansion. Theoretically, the mixes containing the inert limestone filler should reduce the ASR only through the dilution effect. This concept was applied to the mixes in phase B using an inert limestone filler as depicted in Table 3-4. Mix C0 which acted as the control was effectively mix A5 from phase A.

*Table 3-4: Phase C - Investigation of SCMs' ASR mitigation mechanisms*

| Mix | Extender amount and type |
|---|---|
| C0 | 0% inert limestone filler |
| C1 | 20% inert limestone filler |
| C2 | 30% inert limestone filler |
| C3 | 40% inert limestone filler |
| C4 | 50% inert limestone filler |
| C5 | 60% inert limestone filler |

#### 3.2.2.2 Material selection

As mentioned in the literature review, two major contributors to ASR are a sufficient source of alkali and a source of reactive silica. Both components are available through the materials which are used in the mixes, and as such the process of choosing the right materials is of utmost importance when trying to minimise ASR. However, in the context of this research whereby current Western Cape mixes are to be analysed, the process of material selection will be oriented towards assessing the materials which are being used currently in the local construction industry. The datasheet of the materials listed below can be found in Appendix B.

###### 3.2.2.2.1 Cement and cement extenders

At present, a wide variety of constituents are being used in binders which consist mainly of cement, pozzolans and/or inert fillers amongst others. In the Western Cape, there has been an increased use of cement extenders, especially ground granulated Corex slag, with the aim of mainly decreasing clinker content for economic reasons while also improving durability. These blends are already proportioned in specific ratios and are sold in pre-packaged bags. Since the commercially available blended cement bags do not specify exactly the amount of extenders but rather a range, it was found more suitable to actually use the blending ratio and mix the cement extenders and Portland cement. Due to the unavailability of CEM I cement, a close substitute CEM II A-L 52.5N was used. This pre-packaged cement consisted of approximately 6-20% limestone filler; which in the Western Cape is generally 9%. It had a density of 3140 kg/m$^3$ and a sodium equivalent of 0.7% $Na_2O_{eq}$. Pertaining to the cement extenders, class F fly ash and Ground Granulated Corex Slag, GGCS was used. The fly ash is commercially produced and is labelled DuraPozz. It has a density of 2200 kg/m$^3$ and a sodium oxide equivalent of about 1% $Na_2O_{eq}$. The corex slag, obtained from PPC Cement, has a density of 2900 kg/m$^3$ and a sodium oxide equivalent of 0.4% $Na_2O_{eq}$. Finally, an inert filler was used to identify the mechanism via which the supplementary cementitious materials work. Kulubrite 10, which is a commercial limestone filler of Idwala Industrial Holdings, was chosen to replace the extenders in specific mixes. It has a density of 2700 kg/m$^3$.

###### 3.2.2.2.2 Water

Distilled water was used in the concrete mixes to prevent any contamination of the mixes.

###### 3.2.2.2.3 Fine aggregate

One of the aims of this research was to identify the influence of using greywacke crusher sand in the concrete mixes. As such, greywacke crusher sand was present in most mixes in different blending ratios with a secondary fine aggregate, which in this study was chosen to be Philippi dune sand as it is commonly used in the Western Cape. The relative density of greywacke is 2.72 while that of Philippi dune sand is 2.64.

###### 3.2.2.2.4 Coarse aggregate

Coarse aggregates in the form of 9.5mm crushed greywacke was used. The rationale behind this choice was that the coarse aggregate must be at least 3 times smaller than the size of the mould which had a square cross-section of 40mm. As mentioned before, greywacke crushed stone has a relative density of 2.72 while its water absorption is 0.4% (Afrisam 2015).

###### 3.2.2.2.5 Superplasticiser

Where needed, Glenium Ace 456 was used as it has a $Na_20_{eq}$ of less than 1.5%, to improve the workability of the mixes to achieve the needed slumps. The alkali content of the mixes was adjusted to include the releasable alkalis from the superplasticiser.

### 3.2.2.3 Final mix proportions

The design of the mixes was based on the RILEM AAR-2 test standard, with modifications stated in Section 3.2.1. The mixes were proportioned in a ratio of 1 part cement to 2.25 parts dry aggregate. A constant w/b ratio of 0.47, based on the RILEM AAR-2 standard, was used throughout the mixes. Trial mixes were performed to determine the flowability of the mixes which need to fall in the range of 205 to 220 mm (requirement of the RILEM AAR-2 test) for the flow table test (EN 1015-3 [3], refer to Figure 3-3). The trial mixes can be found in Appendix C. The optimised mix proportions are presented in Table 3-5 to Table 3-7.

*Figure 3-3: Flow table test to determine fresh properties of mixes*

*Table 3-5: Final mix proportions of Stage 1 - Phase A*

| Constituent | Mix A0 | Mix A1 | Mix A2 | Mix A3 | Mix A4 | Mix A5 | Mix A6 | Mix A7 | Mix A8 | Mix A9 |
|---|---|---|---|---|---|---|---|---|---|---|
| | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ |
| CEM II A-L 52.5N | 618,9 | 618,9 | 618,2 | 617,4 | 617,2 | 617,0 | 616,8 | 616,6 | 615,9 | 615,1 |
| Water | 290,9 | 290,9 | 290,5 | 290,2 | 290,1 | 290,0 | 289,9 | 289,8 | 289,5 | 289,1 |
| 9.5mm greywacke | - | 835,6 | 834,5 | 833,5 | 833,2 | 833,0 | 832,7 | 832,5 | 831,4 | 830,4 |
| Greywacke crusher | 1392,6 | 557,0 | 445,1 | 333,4 | 305,5 | 277,7 | 249,8 | 222,0 | 110,9 | - |
| Philippi dune sand | - | - | 111,3 | 222,3 | 250,0 | 277,7 | 305,3 | 333,0 | 443,4 | 553,6 |
| Chryso Premia 310 | 1,1 | - | - | - | - | - | - | - | - | - |
| Total | 2303,5 | 2302,4 | 2299,6 | 2296,7 | 2296,0 | 2295,3 | 2294,6 | 2293,9 | 2291,1 | 2288,2 |
| Extra NaOH | 2,4 | 2,4 | 2,4 | 2,4 | 2,4 | 2,4 | 2,4 | 2,4 | 2,4 | 2,4 |

*Table 3-6: Final mix proportions of Phase B*

| Constituent | Mix B1 (40 CS) | Mix B2 (50 CS) | Mix B3 (60 CS) | Mix B4 (20 FA) | Mix B5 (30 FA) | Mix B6 (40 FA) |
|---|---|---|---|---|---|---|
| | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ |
| CEM II A-L 52.5N | 367,8 | 306,0 | 244,4 | 485,5 | 421,3 | 358,2 |
| Water | 288,1 | 287,7 | 287,2 | 285,2 | 282,9 | 280,6 |
| 9.5mm greywacke | 827,6 | 826,3 | 824,9 | 819,2 | 812,5 | 805,9 |
| Greywacke crusher sand | 275,9 | 275,4 | 275,0 | 273,1 | 270,8 | 268,6 |
| Philippi dune sand | 275,9 | 275,4 | 275,0 | 273,1 | 270,8 | 268,6 |
| DuraPozz | - | - | - | 121,4 | 180,6 | 238,8 |
| PPC GGCS | 245,2 | 306,0 | 366,6 | - | - | - |
| Chryso Premia 310 | - | - | - | - | - | - |
| Total | 2280,5 | 2276,8 | 2273,1 | 2257,4 | 2238,9 | 2220,7 |
| Extra NaOH | 1,4 | 1,2 | 0,9 | 1,9 | 1,6 | 1,4 |

*Table 3-7: Final proportions of Phase C*

| Constituent | Mix C1 (limestone 20) | Mix C2 (limestone 30) | Mix C3 (limestone 40) | Mix C4 (limestone 50) | Mix C5 (limestone 60) |
|---|---|---|---|---|---|
| | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ |
| CEM II A-L 52.5N | 490,5 | 427,8 | 365,5 | 303,6 | 242,2 |
| Water | 288,2 | 287,2 | 286,3 | 285,4 | 284,5 |
| 9.5mm greywacke | 827,7 | 825,1 | 822,4 | 819,9 | 817,3 |
| Greywacke crusher sand | 275,9 | 275,0 | 274,1 | 273,3 | 272,4 |
| Philippi dune sand | 275,9 | 275,0 | 274,1 | 273,3 | 272,4 |
| Inert filler | 122,6 | 183,3 | 243,7 | 303,6 | 363,2 |
| Chryso Premia 310 | - | - | - | - | - |
| Total | 2280,7 | 2273,5 | 2266,3 | 2259,1 | 2252,0 |
| Extra NaOH | 1,9 | 1,7 | 1,4 | 1,2 | 0,9 |

## 3.3 Stage 2: impact of ASR on compressive strength

The compressive strength test is one of the most important mechanical properties governing the choice of concrete mixes in the construction industry. The test was performed on 50 mm cubes subjected to two different curing conditions, for all the concrete mixes described in Section 3.2, to determine the effect of ASR gel formation on this property. The first curing condition investigated, constituted of storing the cubes in a water bath at 22-25˚C for a period of 28 days. The second curing condition involved storing the specimens in conditions similar to the AMBT test, whereby the concrete samples were kept in a 1M NaOH solution at 80˚C for 28 days, in order to cause ASR reaction in the specimens. After the 28 days period, the samples were removed from their curing environment, their dimensions and mass recorded, and eventually tested for the compressive strength based on the SANS 5863:2006 standard.

## 3.4 Stage 3: subsidiary testing

With the aim of further understanding the mechanisms involved and the impact of ASR gel formation, the critical mixes identified in Stage 1 of the testing regime, depicted in Table 3-8, were subjected to additional testing procedures as described in this section. It is to be pointed out that the following tests were carried out as subsidiary testing with limited sample size and consequently produced limited data. As such, the results should be read objectively from a qualitative perspective.

*Table 3-8: critical mixes identified from Stage 1*

| Mix | Variable | |
|---|---|---|
| | Type | Description |
| A0 | Control | Standardised AAR-2 test |
| A5 | Reactive fines content | 50% crusher sand and 50% dune sand |
| B2 | Extender type | 50% GGCS |
| B4 | Extender type | 20% fly ash |
| C1 | Extender type | 20% inert limestone filler |
| C4 | Extender type | 50% inert limestone filler |

### 3.4.1 Optical light microscopy

Optical light microscopy was performed on the concrete samples with the main aim of identifying the distribution of ASR gels in the critical mixes of Stage 1. A technique developed (Guthrie & Carey 1997) was employed as it does not produce any toxic waste contrary to the more common uranyl acetate test. This method involves the use of two chemical compounds with the objective of identifying ASR gel products containing potassium and calcium ions. Through the research conducted by Guthrie & Carey (1997), it was found that sodium cobaltinitrite, $Na_3Co(NO_2)_6$ reacts with the potassium in K-rich ASR gels to form a yellow precipitate, while the second compound Rhodamine B, $C_{28}H_{31}N_2O_3Cl$, tends to be absorbed by Ca-rich but K-poor ASR gel products producing a pink colour. As described in Chapter 2, the Ca-rich gel, C-N(K)-S-H is the non-swelling gel in ASR which interacts with the swelling gel, N(K)-S-H, to cause expansion. Both the swelling and non-swelling gels contain K ions and as such this test does not differentiate between the two. The experimental technique, derived from this research, was used on the six mixes identified in Table 3-6 in the sequence listed below, recommended by Guthrie & Carey (1997):

- The surface of the concrete sample was rinsed with deionised water;
- The sodium cobaltinitrite solution was applied on the surface and allowed to rest for 45 seconds before being rinsed again using deionised water;
- The rhodamine B solution was then applied and allowed to rest for 45 seconds;
- The surface was again rinsed with deionised water and dabbed to remove any further surface water; and

- The specimens were analysed under a light microscope (WILD Photomakroskop M400 illustrated in Figure 3-3) at varying magnification levels to best identify changes associated with ASR gel formation.

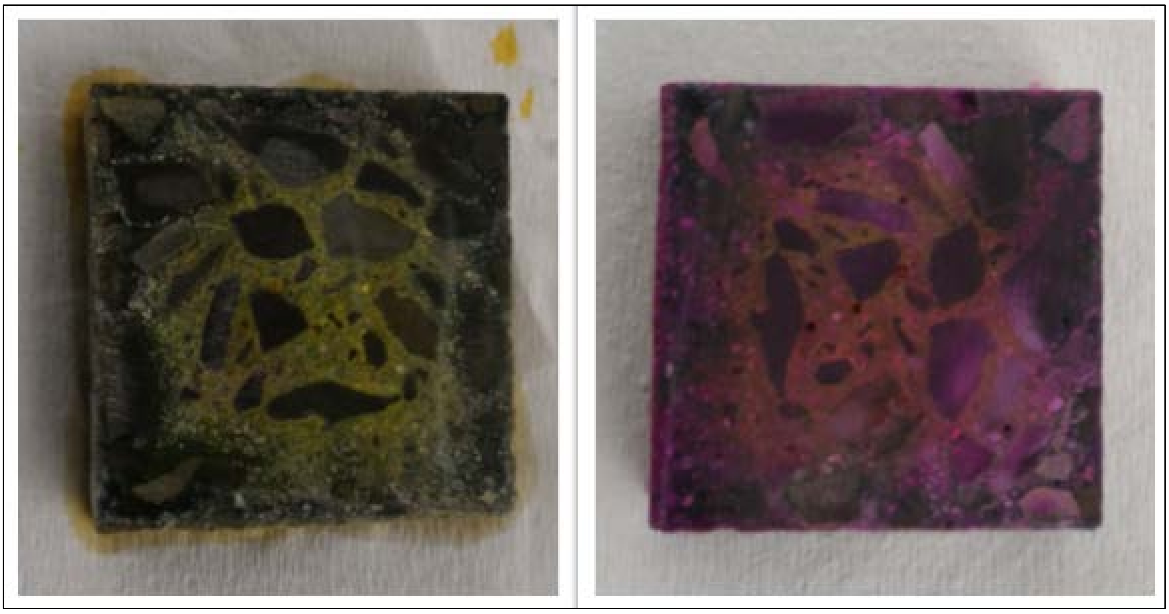

*Figure 3-4: After application of sodium cobaltinitrite (left), after application of rhodamine B (right)*

*Figure 3-5: WILD Photomakroskop M400*

### 3.4.2 SEM and EDS

Since the thickness of most cracks associated with ASR, in the early stages of gel formation, is in the region of nanometres, the light microscopy option would not be suitable for analysing crack distribution in ASR affected samples. An electron microscope (ZEISS LEO 1450) was used for that purpose. The samples, used for the AMBT test in stage 1, were cut into approximately 15mm cubes. For each mix, two samples were taken, one close to the surface of the prism and one at the centroid. These were then sealed in a resin compound (Epofix resin), vacuum dried and eventually polished gradually with the finest grit being of 0.25 μm. The smooth surface of the sample was then carbon impregnated before being analysed in the scanning electron microscope. Energy dispersive spectroscopy (EDS) was also performed on key points, such as in cracks or around the aggregates, to identify the elemental composition of the material at those specific locations.

### 3.4.3 Pore expression and ICP-OES

This technique, described by Barneyback and Diamond (1981), was used to extract the pore solution from the concrete samples which could be further analysed for chemical composition. The mixes in Table 3-6 were cast into 50 mm cubes and stored in distilled water at 80 °C for 28 days. The samples were then removed from the water bath and allowed to air dry for 3 hours. They were then loaded in the pore expression device for the extraction of the pore solution. The pore expression device as depicted in Figure 3-4 consists of a plunger which is used to compress the samples in a confining cylinder. A load of 450 kN was applied and maintained for about 5 minutes to extract the solution. A grooved ring at the bottom of the base plate channels the pore solution into a drilled hole in the base, which is connected to a syringe. This collection mechanism minimised any contact with the atmosphere and hence prevented any oxidation of the components present in the solution. The collected samples were then filtered through a 45μm filter paper and tested for their chemical composition (mainly Na, K, Ca and Al ions) using an inductively coupled plasma optical emission spectrometer.

*Figure 3-6: Pore expression device*

## 3.5 Stage 3: long-term performance testing

Performance tests generally have a longer experimental period which may span over years depending on the chosen test method. However, the results obtained from these tests are deemed more reliable than the indicator tests and are usually performed to confirm the results obtained from the latter. As such, the critical mixes observed in Stage 1 of this research project were adapted to produce five ‘real-life’ mixes, reported in Section 3.5.3, which would be subjected to the performance test. The materials used for this stage of testing is the same as for Stage 1. The choice of performance test is presented in Section 3.5.1.

### 3.5.1 Performance test comparison and selection

Pertaining to the performance tests, the criteria for selection was less complex than for the indicator test as the job mix can be used in the experimental procedures of all the specified tests.

*Table 3-9: long-term performance tests comparison*

| Standard | Field performance | ASTM 1293-08b | RILEM AAR-3 | RILEM AAR-4.1 | Norwegian test |
|---|---|---|---|---|---|
| Testing period (years) | +2 | 1-2 | 1-2 | 0.5 | 1-2 |
| Temperature (˚ C) | ambient | 38 | 38 | 60 | 38 |
| X-section of specimen (mm) | 100x100 | 75x75 | 75x75 | 75x75 | 100x100 |
| Alkali leaching | Minimal | Pronounced | Pronounced | Pronounced | Minimal |

| 🟩 | 🟨 | 🟥 |
|---|---|---|
| → More desirable to least desirable | | |

From Table 3-9, the field performance test would be the ideal test to perform disregarding the time factor. The only test which can be completed within a relatively short period of time is the RILEM AAR-4.1 test. However, in order to do so, the test makes use of an elevated temperature which does not reflect normal conditions to which structures are normally subjected to. Moreover, as can be seen from Table 3-9, alkali leaching is a major issue in this test mainly due to the smaller specimen size. The Norwegian test on the other hand made use of a bigger specimen size to minimise the effects of alkali leaching. It was decided that a combination of the two tests would be the most suitable option for this research project. The procedure of the RILEM AAR-4 would be followed but the specimen size would be increased to 100 mm cross sectional area to match the Norwegian test. Long term field testing will also be performed on these mixes. Due to the time constraint of this research, only the preliminary results of the field performance test will be presented for comparative purposes to identify any expansion trend.

#### 3.5.1.1 Performance test procedure

As described above, two performance tests namely the RILEM AAR-4 and the field testing were chosen for this study. The only modification employed was the use bigger specimen size for the RILEM AAR-4 method.

The procedure followed for the modified RILEM AAR-4 test was as follows:

- Three specimens of 100×100×200mm were cast for each mix;
- After 24 hours, the specimens were demoulded, marked and strain targets were placed on two opposite longitudinal faces;
- An initial target placement, $L_i$, reading to the nearest 0.001mm was taken;
- Specimens were suspended over a water bath, of depth 35±5mm, in a sealable container and stored in an oven at 60±2˚C;
- Subsequent expansion readings were taken at 5, 10, 15 and 20 weeks of age. 24 hours prior to each measurement, the specimens were removed and kept in a room at 20±2˚C and relative humidity not less than 50%.

*Figure 3-7: AAR-4 test specimen (left), AAR-4 storage setup (right)*

A relatively similar process was employed for the field testing with the exception that the samples were kept outside, exposed to climatic conditions. Specimens of size 100×100×200mm were cast, demoulded after 24 hours and strain targets placed. The same age of reading was employed for the field testing specimens as for the RILEM AAR-4 test to allow for comparison. It is to be noted that the period of this test spans for at least 2 years and as such only preliminary test results were available at the time of writing.

### 3.5.2 Test variables

The test variables which were investigated through the five mixes are depicted in Table 3-10. Mix D0 was the control with the fine aggregates consisting of only Philippi dune sand. Mix D1 was a variant of the control whereby 50% of the fine aggregate consisted of greywacke crusher sand while mix D2 was a variant of the former with the inclusion of NaOH solution to boost the alkali content to 1% $Na_2O_{eq}$. Mixes D3 and D4 were variants of mix D1 whereby part of the cement was substituted by fly ash and GGCS at 20% and 50% by mass respectively.

*Table 3-10: long-term testing mixes*

| Mix | Variable | |
|---|---|---|
| | Type | Description |
| D1 | Control | 100% CEM II A/L 52.5N & only Dune Sand (DS) |
| D2 | Reactive fines content | 100% CEM II A/L 52.5N & 50/50 DS/CS* |
| D3 | Alkali content | 100% CEM II A/L 52.5N boosted alkali content, with 50/50 CS/DS |
| D4 | Extender type | 80% CEM II A/L 52.5N & 20% fly ash with 50/50 CS/DS |
| D5 | Extender type | 50% CEM II A/L 52.5N & 50% GGCS with 50/50 DS/CS |

*Note: * DS stands for Philippi Dune sand and CS stands for Greywacke crusher sand*

### 3.5.3 Mix design

The mixes were designed primarily using the C&CI method (refer to Appendix D for the calculation sheets). However, upon trial testing it was deemed more appropriate to fix the coarse aggregate (19mm greywacke stone) content to 1050 kg/m$^3$ as some of the mixes showed signs of segregation. The final mix compositions are given in Table 3-11.

*Table 3-11: Final mix proportions of long-term mixes*

| Constituent | Mix D1 | Mix D2 | Mix D3 | Mix D4 | Mix D5 |
|---|---|---|---|---|---|
| | kg/m³ | kg/m³ | kg/m³ | kg/m³ | kg/m³ |
| CEM II A-L 52.5N | 298,4 | 298,4 | 298,4 | 264,3 | 165,2 |
| Water | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 |
| 19mm greywacke | 1050,0 | 1049,9 | 1049,9 | 1049,9 | 1049,9 |
| Greywacke crusher sand | - | 447,7 | 447,7 | 422,3 | 428,3 |
| Philippi dune sand | 884,7 | 447,7 | 447,7 | 422,3 | 428,3 |
| DuraPozz | - | - | - | 66,1 | - |
| PPC GGCS | - | - | - | - | 165,2 |
| Total | 2418,1 | 2428,6 | 2428,6 | 2409,8 | 2421,8 |
| Extra NaOH | - | - | 1,2 | - | - |

# 4 Results and discussion

## 4.1 Overview of chapter 4

This chapter puts forward and discusses the results from the experiments detailed in Chapter 3. Section 4.2 focuses on the results of the AMBT tests performed on the mixes. This section further details the effect of using reactive fine aggregates in the concrete mix, the influence of using cement extenders and the mechanisms through which cement extenders mitigate ASR in subsections 4.2.1 to 4.2.3 respectively. Thereafter, Section 4.3 details the results of the compressive strength test with the aim of demonstrating the impact of ASR gel formation on this mechanical property. Section 4.4 details the results of the subsidiary tests as described in Section 3.4. Lastly, Section 4.5 discusses the preliminary results obtained from the long-term performance testing, while drawing comparisons with the AMBT test results where possible. Conclusions and recommendations derived from these results are presented in Chapter 5. Detailed results of the experimental regime are provided in Appendix E to H.

## 4.2 AMBT test

### 4.2.1 Effect of using reactive fine aggregate

The AMBT tests were performed on prismatic specimens, as described in Section 3.2.1. Measurements of the increase in length were taken at 14 and 28 days. As described in Section 3.2.2.1.1, the results of this phase of testing were refined in the range of 40-60% reactive greywacke fine aggregate to obtain a better representation of the maximum expansion. Figure 4-1 illustrates the preliminary results obtained from the first set of mixes and Figure 4-2 illustrates the refined results around the maxima. The error bars indicate the maximum and minimum values obtained for each mix. The detailed results of these mixes are provided in Appendix E1.

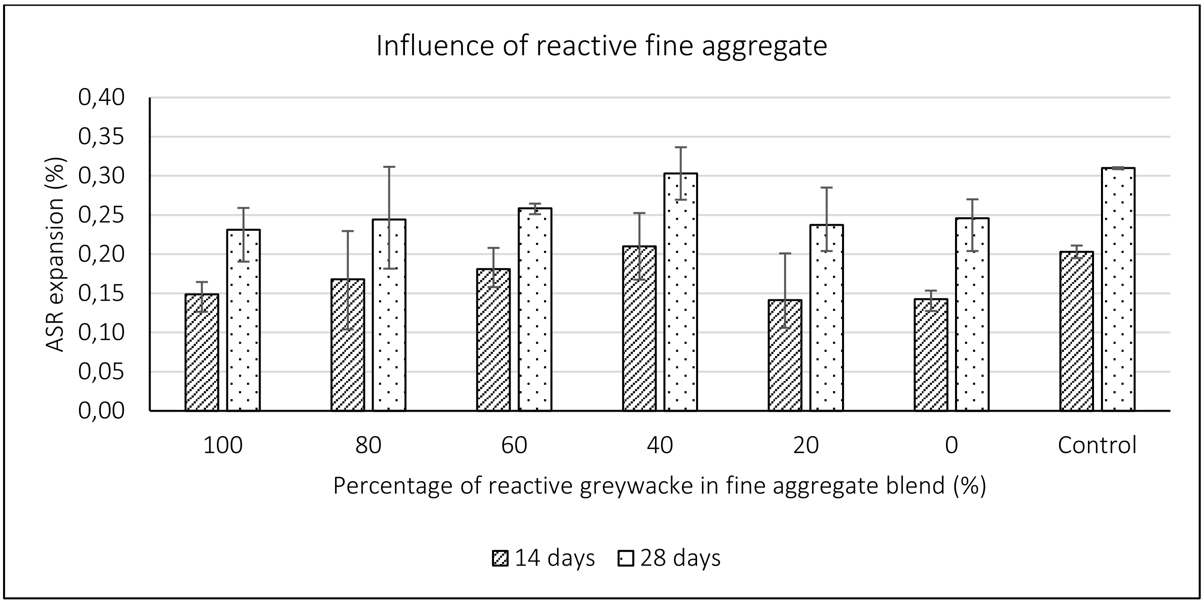

*Figure 4-1: Stage 1 - Phase A - AMBT test results at different reactive aggregate replacement levels*

Comparing the results, it was found that all the mixes tested were classified as 'reactive' based on the AAR-2 specifications, that is an expansion greater than 0.10% at 14 days. The control mix and mix with 40% greywacke in the fine aggregate blend are further described as 'deleteriously reactive' as their expansion exceeded 0.20%, while the other mixes are described as 'slowly reactive'.

Observing the results in the range of 0% to 100% greywacke crusher sand in the fine aggregate blend, there was an initial increase in the expansion observed, which peaked and then reduced again. This phenomenon is defined as the 'pessimum' proportion effect, as described in Section 2.3.3.2. As the reactive aggregate content initially increased, the expansion increased, presumably from the formation of more gel products and subsequently more cracked aggregates. This trend followed up to a maximum which is described as the pessimum, occurring around 40% greywacke crusher sand in the context of this research. Beyond this point, further addition of reactive aggregate increases the amount of mature alkali silicate which consumes most of the $Ca(OH)_2$ in the pore solution to form fragmental calcium alkali silicate. As a result, the amount of gel products decreased and the ASR expansion observed also decreased (Ichikawa & Miura 2007). A statistical analysis (t-test) showed that there was no statistically significant difference, at a confidence level of 95%, between any two sets of mixes, except the control mix. However, from an engineering perspective, the implications would be significant. For instance, comparing the mix with 20% and 40% reactive fine aggregate, the former was classified as 'slowly reactive' while the latter would be classified as 'deleteriously reactive', representing a pass and fail scenario respectively.

The control in this testing regime, containing only reactive greywacke crusher sand graded to the AAR-2 specifications, had the second highest expansion at 14 days and highest expansion at 28 days. It was noted that the 'micro-concrete' mixes tended to have lower expansions than the control. Nevertheless, the 'micro-concrete' mix with 40% greywacke crusher sand was observed to have a slightly higher expansion than the control at 14 days. Since the former had overall a lower amount of reactive aggregates, the results suggested that there might be a better gel distribution in the control mix and that the higher expansion in the 40% mix may be due to more localised gel products. By contrast, comparing the 'micro-concrete' mix with 100% reactive crusher sand in the aggregate blend and the control, which both had the same mass of reactive aggregate, it was observed that the control mix had a higher expansion. This points to the fact that the grading of the aggregate does have a significant impact on the results of the AMBT test. Multon et al. (2010) and Ramyar & Topal (2005) have reported the effects of varying the size of aggregate and described different 'pessimum' size ranges whereby the expansion is maximum. Gautam et al. (2017) carried out performance tests on Spratt aggregate and deduced that even when aggregate grading was varied within the acceptable limits of the compressive strength test, significant differences were observed in the expansion values. This suggests that the aggregates should not be graded to specific standardised specifications. They should rather be tested 'as is' since the mineralogy, diffusivity of alkali or fracture mechanics may vary across different types of aggregates.

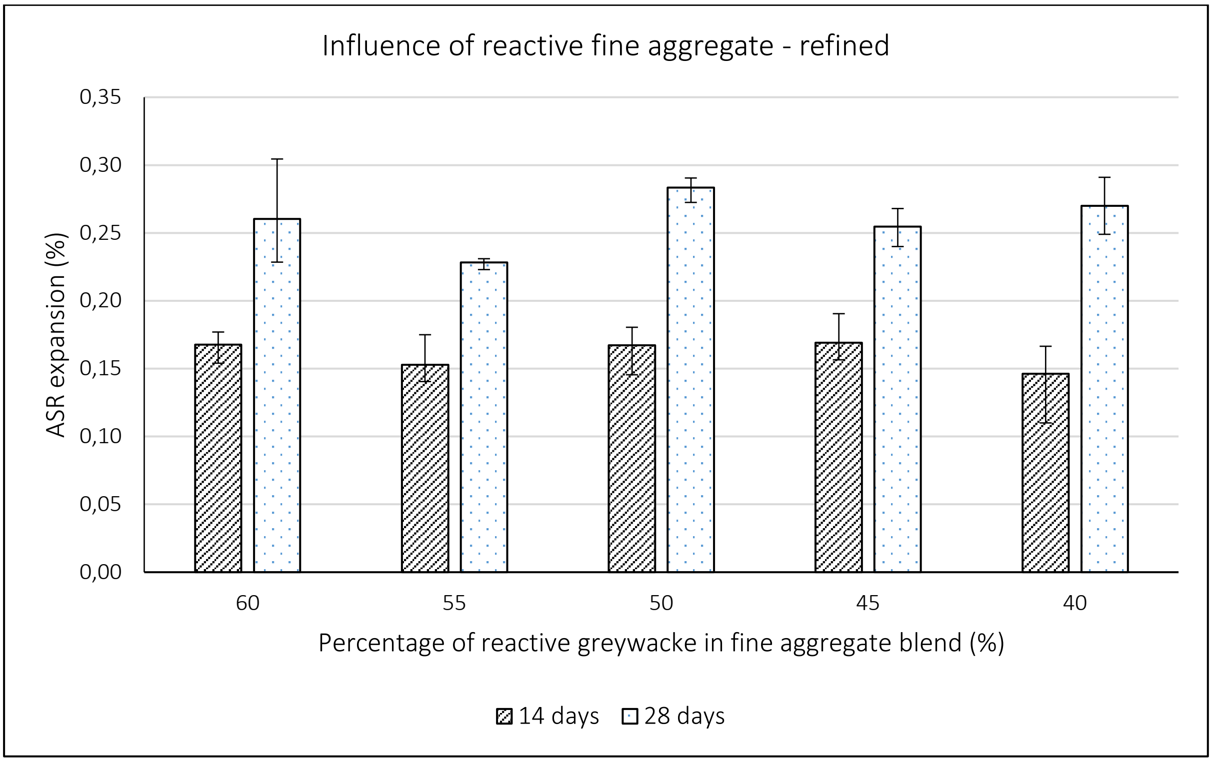

*Figure 4-2: Phase A AMBT test results at different replacement levels - refined*

In the refinement stage represented in Figure 4-2, the 'pessimum' proportion effect was less apparent, and the statistical analysis showed that that there was no significant difference between the results obtained. The mix containing 50% reactive greywacke crusher sand had the maximum expansion at 28 days and was therefore deemed to be the most reactive, and was used in further testing with the cement extenders. It was noted that the results for the mix with 60% and 40% reactive crusher sand from the first stage and the refinement stage had different results. A t-test, with confidence level of 95%, performed on the sets of results showed that the results were not statistically different. This issue of repeatability for the AAR-2 has been pointed out in the EU Partner Programme and published in the RILEM Recommendations (RILEM 2016). However, in the context of this research, the coefficient of variation was greater than the ones observed in the EU Partner Programme. This may have arisen due to the addition of coarse aggregates in the 'micro-concrete' mixes which would further decrease the degree of homogeneity.

### 4.2.2 Influence of cement extenders

The AMBT tests were performed on prismatic specimens, as described in Section 3.2.1. As described in Section 0, 'micro-concrete' mix A5, containing 50% reactive greywacke crusher sand was taken as the control. The 6 mixes in this phase of testing were made up by substituting fly ash and corex slag at different replacement levels. Measurements were again taken at 14 and 28 days.

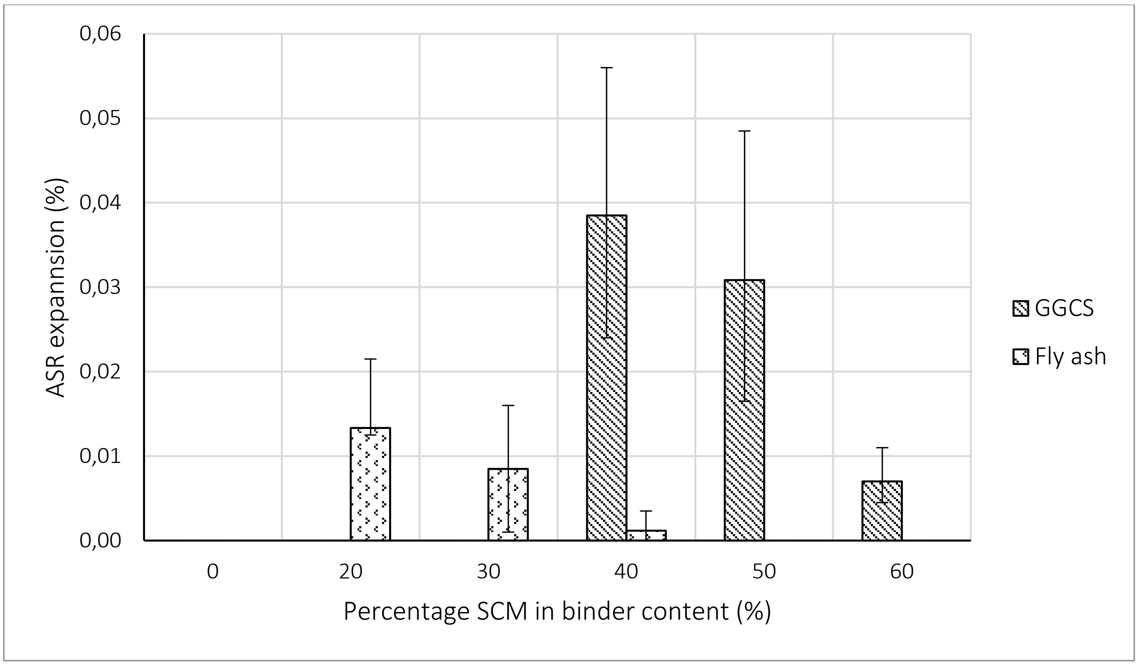

*Figure 4-3 and*

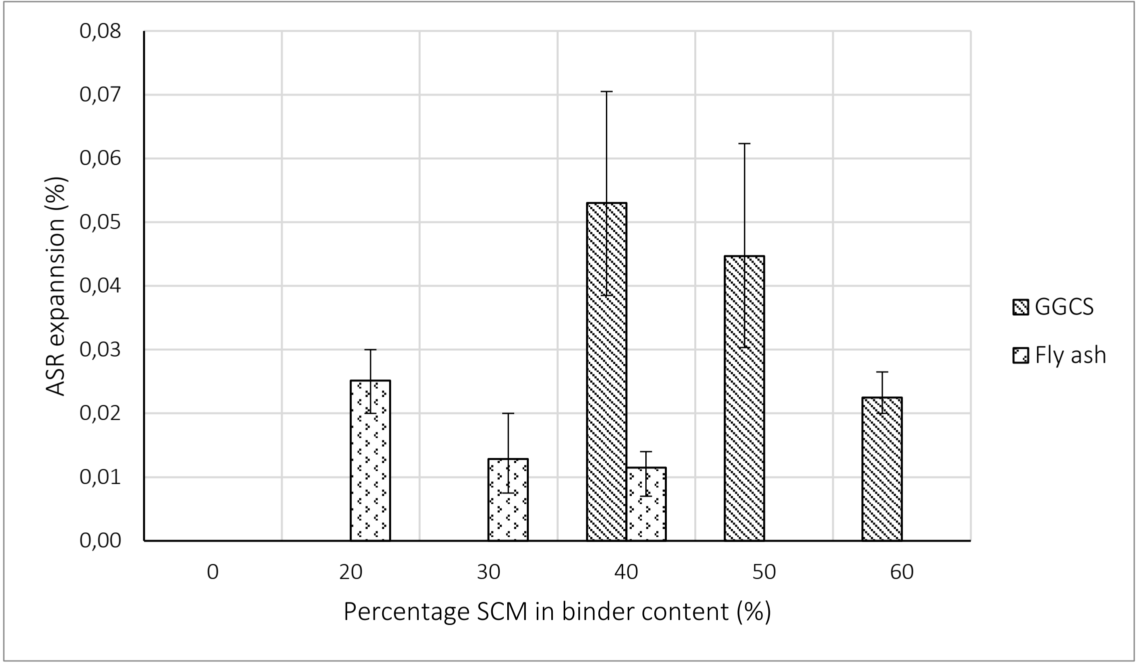

Figure 4-4 illustrate the results obtained for the AMBT test performed on these mixes at 14 days and 28 days respectively. The error bars indicate the range of values obtained for each mix. The detailed results of these mixes are provided in Appendix E2.

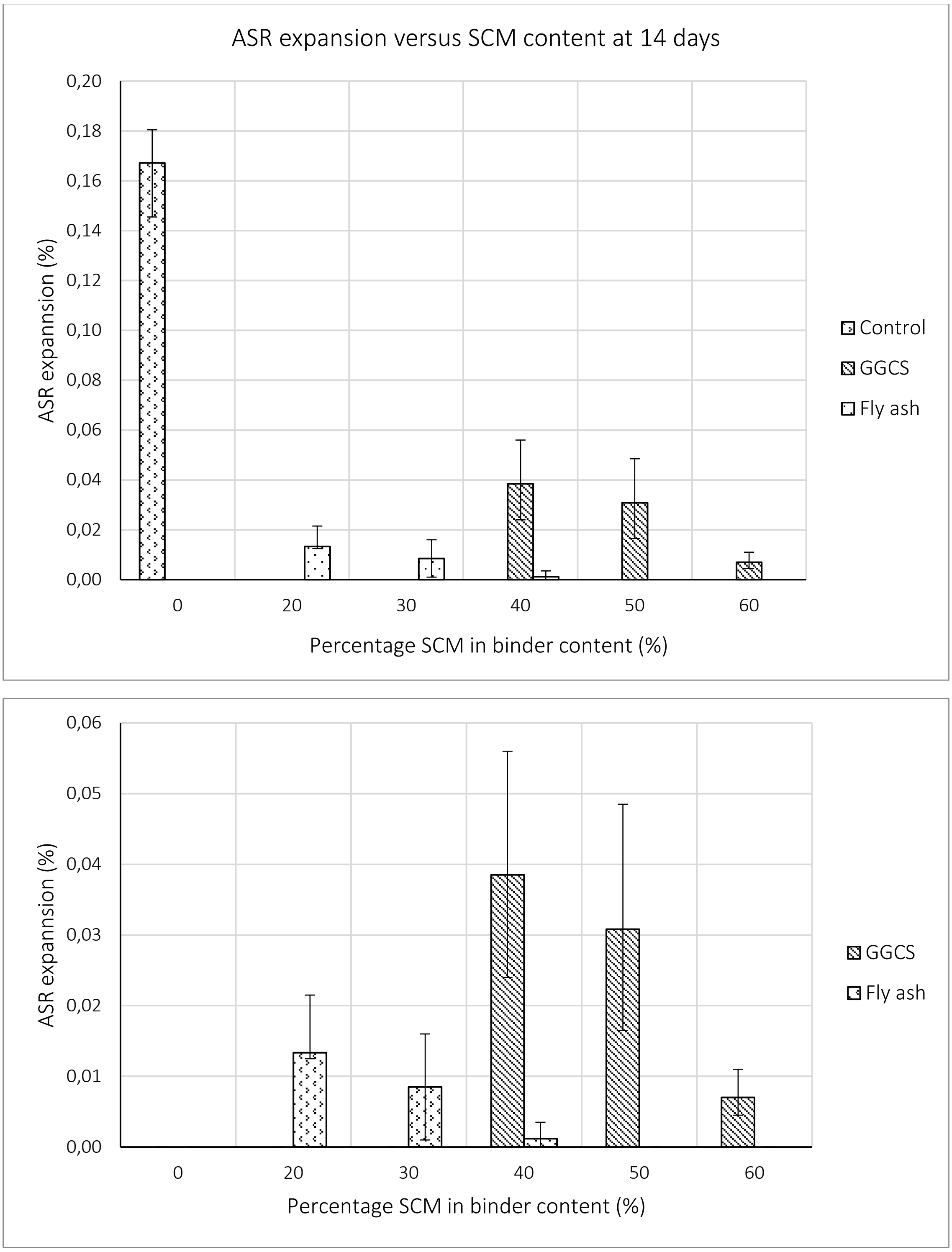

*Figure 4-3: Influence of cement extender content on expansion in the AMBT test at 14 days*
*Note: the second graph is a magnified view of the first one*

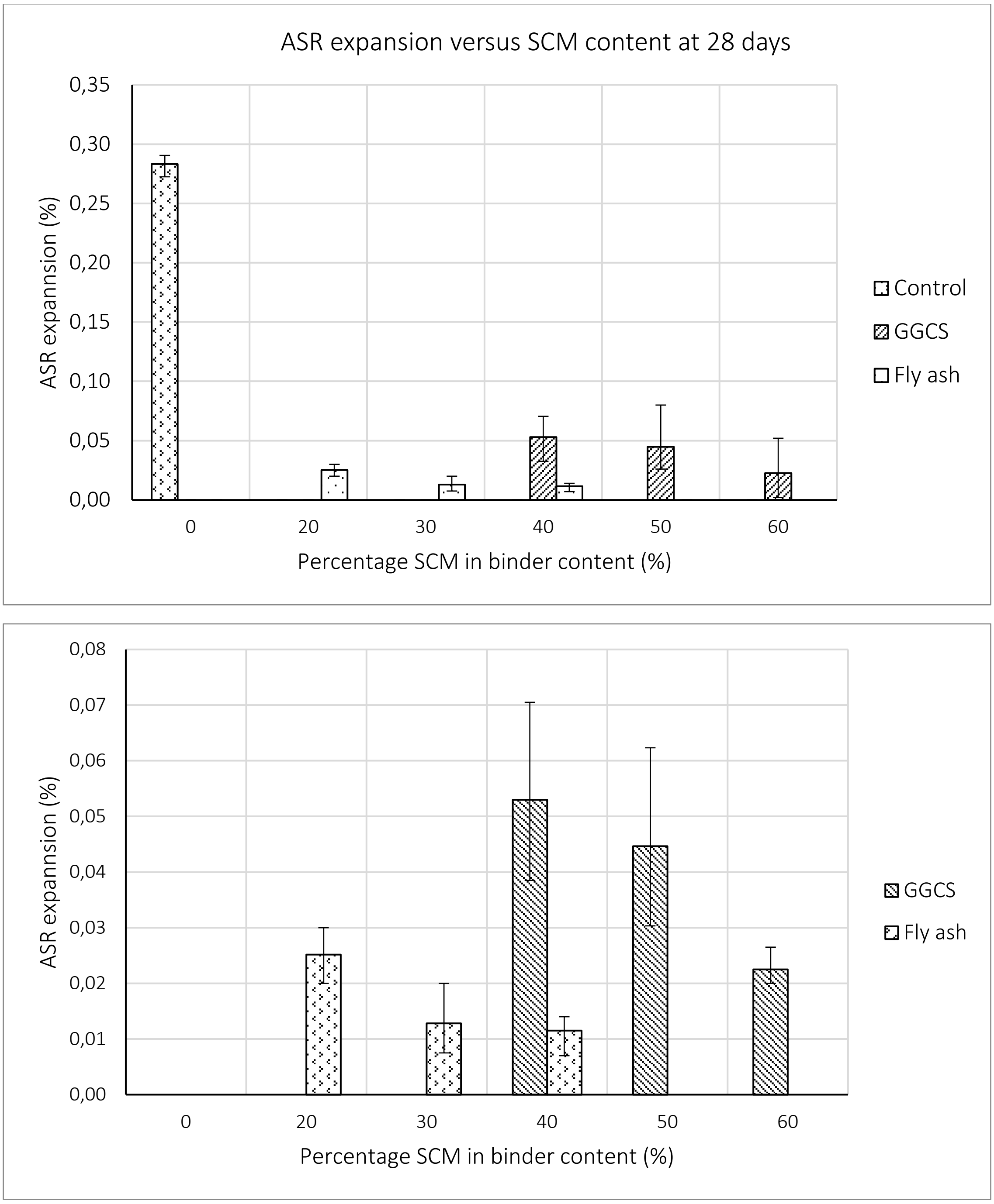

*Figure 4-4: Influence of cement extender content on expansion in the AMBT test at 28 days*
*Note: the second graph is a magnified view of the first one*

From the results, both cement extenders were effective at controlling ASR expansion even at the respective lowest replacement levels used. The expansions obtained from the mixes containing the cement extenders were significantly below the 0.10% expansion limit and therefore the mixes were classified as 'non-reactive' with respect to ASR. The decrease in expansion can be attributed partly to the alkali dilution provided by the substitution of cement with cement extenders. This decreased the amount of releasable alkali available for the ASR reaction. The corex slag used had a $Na_2O$ eq of 0.4% which is lower than that of the cement used, which was 0.7%. The fly ash on the contrary had a $Na_2O$ eq of 1.0%, however the amount of releasable alkalis is lower than that of the cement. The releasable alkali content is generally around 0.2-0.5% $Na_2O$ eq for South African fly ashes (Grieve 2009). Consequently, decreasing the alkali content in the pore solution. Moreover, the cement extenders also undergo reaction with the alkali in the pore solution, known as the reaction effect, which further decreases the alkali available for ASR gel formation. Since the siliceous cement extenders are very fine and consequently have large surface areas, they preferentially react with alkali hydroxide to form alkali silicate which in turn reacts with $Ca(OH)_2$. Therefore, less $Ca(OH)_2$ is available for ASR reaction (Ichikawa 2009). Shafaatian et al. (2013) further reported that the addition of cement extenders increases the acidity of silanol (Si-OH) groups and/or develops alkali attractive surface charges on the surface of low C/S C-S-H which further binds alkali from the pore solution.

The results also show that the fly ash was more effective at controlling ASR expansion than the corex slag. 40% Class F fly ash reduced the expansion by approximately 16 times while the same amount of corex slag decreased the expansion by approximately 4 times. This may be attributed to the fact that fly ash has a lower CaO content than corex slag. Shehata & Thomas (2000) demonstrated that an increase in CaO content led to an increase in ASR expansion. Moreover, the fly ash has a higher alumina ($Al_2O_3$) content than the corex slag. Shafaatian et al. (2013) reported that dissolved Al ions form C-A-S-H which considerably increases the alkali binding capacity of the reaction products.

### 4.2.3 Comparison of SCMs and LS fillers

The AMBT tests were performed on prismatic specimens, as described in Section 3.2.2. As described in Section 4.2.1, 'micro-concrete' mix A5, containing 50% reactive greywacke crusher sand was taken as the control. The subsequent 5 mixes in this phase of testing were made up by substituting part of the cement with a nominally 'inert' limestone filler, namely 'Kulubrite 10'. The replacement levels chosen was similar to those used for the cement extenders to allow for comparison. Figure 4-5 illustrates the results obtained for the AMBT test performed on these mixes at 14 and 28 days, while Figure 4-6 illustrates the difference between using an inert filler and cement extenders on ASR expansion at 14 days. The error bars indicate the range of values obtained for each mix. The detailed results of these mixes are provided in Appendix E3.

From Figure 4-5, substituting limestone filler, Kulubrite 10, in the concrete mix resulted in a decrease in the ASR expansion with respect to the control mix. The expansions observed for the mixes containing the limestone filler were generally close to the 0.10% expansion limit at 16 days, and could therefore be classified as 'slowly reactive' based on the AAR-2 specifications. From Figure 4-6, the inert filler is not as effective in mitigating ASR as the fly ash or the corex slag. This is because the inert filler only contributed to diluting the alkali of the binder and did not contribute to any further alkali reduction. At 40% replacement level, the expansion for the limestone filler was 55%, the corex slag was 23% and the fly ash was 1% of the original expansion of the control mix. This shows that the reaction effect plays a significant role in mitigating ASR when using cement extenders. Additionally, it was observed that at a replacement level of 60% limestone filler, there was a slight increase in the expansion. As the scope of the project was limited to the specified replacement levels, it is still ambiguous whether this was a trend which would continue as more limestone is added. If it would, one possible hypothesis could be that the amount of Ca ions released from the limestone contributed to increasing the thickness of the reaction rims around the aggregates. From a mechanical point of view, more limestone implied that the matrix was more porous. This may have facilitated the internal transport of alkalis to the aggregate while it could have also resulted in greater crack propagation in the specimens. This issue however did not lie within the scope of this project and therefore would have to be investigated further before any conclusions could be derived.

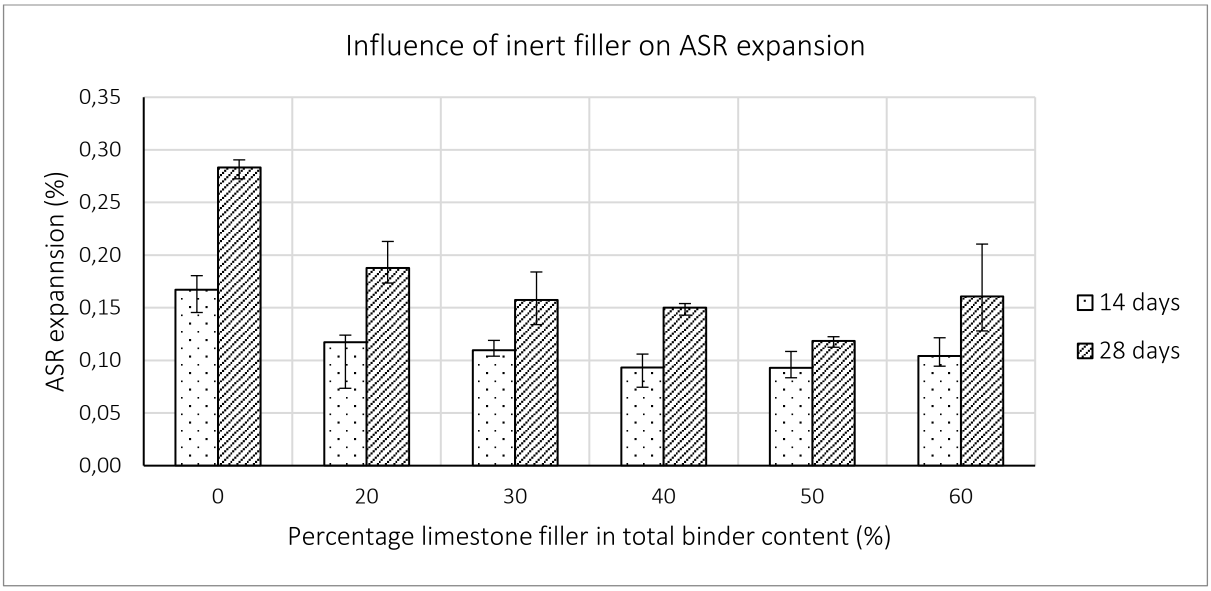

*Figure 4-5: Influence of inert filler on ASR expansion in the AMBT test at 14 and 28 days*

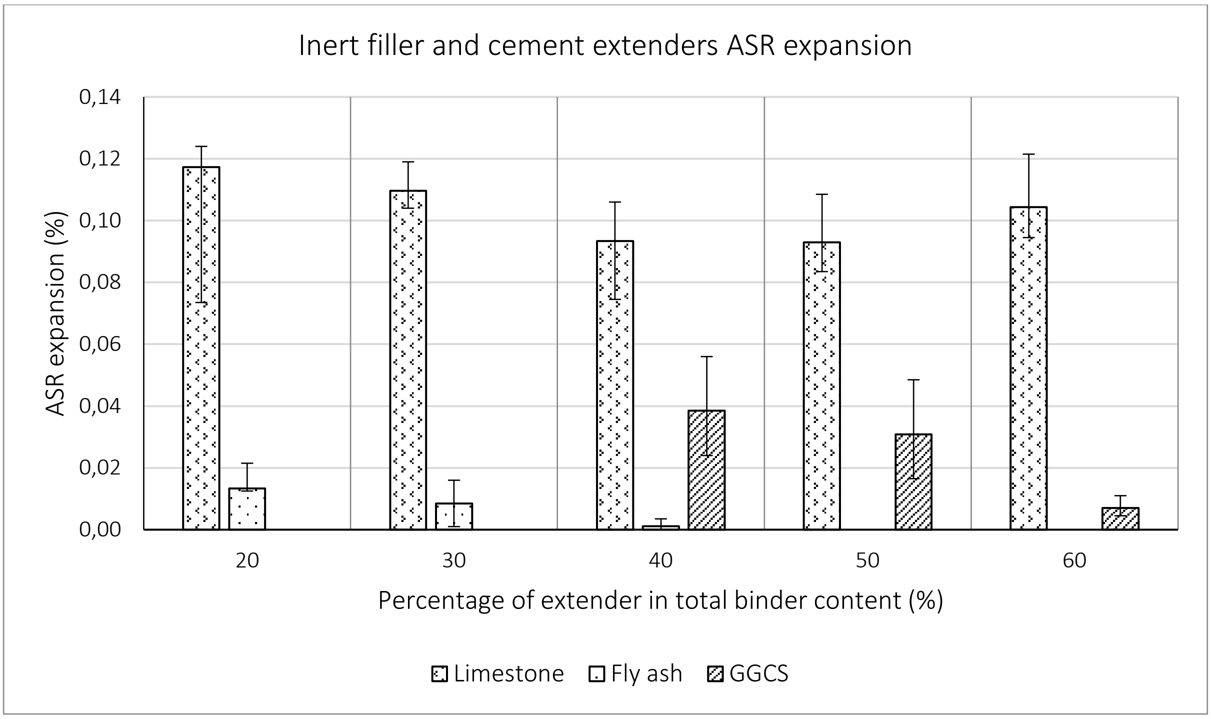

*Figure 4-6: Comparison between the influence of inert filler and cement extenders in the AMBT test at 14 days*

## 4.3 Compressive strength test results

The mechanical response of ASR affected concrete is highly dependent on the aggregate properties such as the reactivity, quantity, size and particle size distribution (Yurtdas et al. 2013). Islam & Ghafoori (2015) supported this view through experiments on differently reactive aggregates, showing that the compressive strength deterioration was highly affected by the reactivity of the aggregates. Moreover, the available moisture, available alkali content and temperature all affect ASR reaction kinetics and thus the extent of deterioration (Giaccio et al. 2008). In this research, the quantity of reactive aggregates was varied in Phase A by varying the crusher sand content, while the alkali content was varied in Phase B and C using cement extenders and fillers as part of the binder. Compressive strength tests were performed on the mixes as described in Section 3.3 using 50 mm cubes at 28 days of age. The specimens were subjected to two different curing conditions, namely water-cured at 22-25℃, and alkali-cured in a 1M NaOH solution at 80℃. Section 4.3.1 discusses the compressive strength test results of Phase A specimens. Section 4.3.2 discusses the compressive strength results of Phase B and Phase C in which cement extenders and fillers were added to the mix. Detailed results of the compressive strength test are provided in Appendix F.

### 4.3.1 Influence of varying reactive aggregate content

Phase A aimed at determining the effect of combining reactive greywacke crusher sand, at different replacement levels in the total sand blend, and reactive 9.5mm greywacke aggregate, forming a ‘micro-concrete’. In total, 10 different mixes, with varying crusher sand levels, were tested for this phase. As described in Section 3.2.2.1.1, the fine aggregate variation stage was refined in around the optimum expansion observed. Consequently, 3 mixes were added and the mixes containing 40% and 60% crusher sand in the total sand blend were repeated. Figure

4-7 and Figure 4-8 illustrate the compressive strength results of the preliminary mixes and refined mixes in Phase A respectively. The error bars on the columns indicate the maximum and minimum values obtained for the compressive strength for each mix. Detailed results of these tests can be found in Appendix F1.

The water cured specimens in this research served as reference to compare with the ASR affected specimens. From the results in Figure 4-7 and Figure 4-8, there is no clear trend which could be identified for the compressive strength when varying the levels of crusher sand in the concrete mixes cured in the water bath at 22-25℃. This could be attributed to the fact that there are several factors such as packing density, porosity and uniformity of the mix amongst others which impact these results (Perrie 2009). However, upon subjecting the specimens to a condition which promotes ASR gel formation, that is in a 1M NaOH solution at 80℃, there was a clear reduction in the compressive strength in each alkali-cured mix relative to its water cured control. This decrease in strength is mainly attributed to the formation of micro-cracking in the matrix and aggregate particle cracking. As the ASR reaction progresses, gel products are formed in and around the aggregates and fill in the voids in the matrix. The presence of moisture then induces the swelling of these gel products, which in turn exerts tensile forces and causes cracking. Microscopical analysis of the control mix and mix A5, containing 50% crusher sand in the total sand blend, identified as part of the critical mixes in Section 3.3 and discussed further in Section 4.4.2, showed significant micro-cracking in and around the aggregates in the specimens tested. The greatest percentage reduction in strength in the preliminary mixes of Phase A, depicted in Figure 4-7, was 26.2% for the mix containing 40% crusher sand in the total sand blend (Mix A3). The same mix was observed to have the greatest expansion in the AMBT test as described in Section Effect of using reactive fine aggregate, further supporting the relationship between compressive strength and ASR expansion. Electron micrographs presented in Section 4.4.2 also qualitatively supported this claim. Pertaining to repeatability, it was found that the mix containing 40% crusher sand had a marginally lower compressive strength in the refined stage. This decrease could be attributed to factors such the particle size distribution of the aggregates and compaction of the mix, which would in turn affect the porosity of the specimen. Nevertheless, the decrease in compressive strength of that mix in the two phases were 26% and 20% respectively, which indicates reasonable consistency.

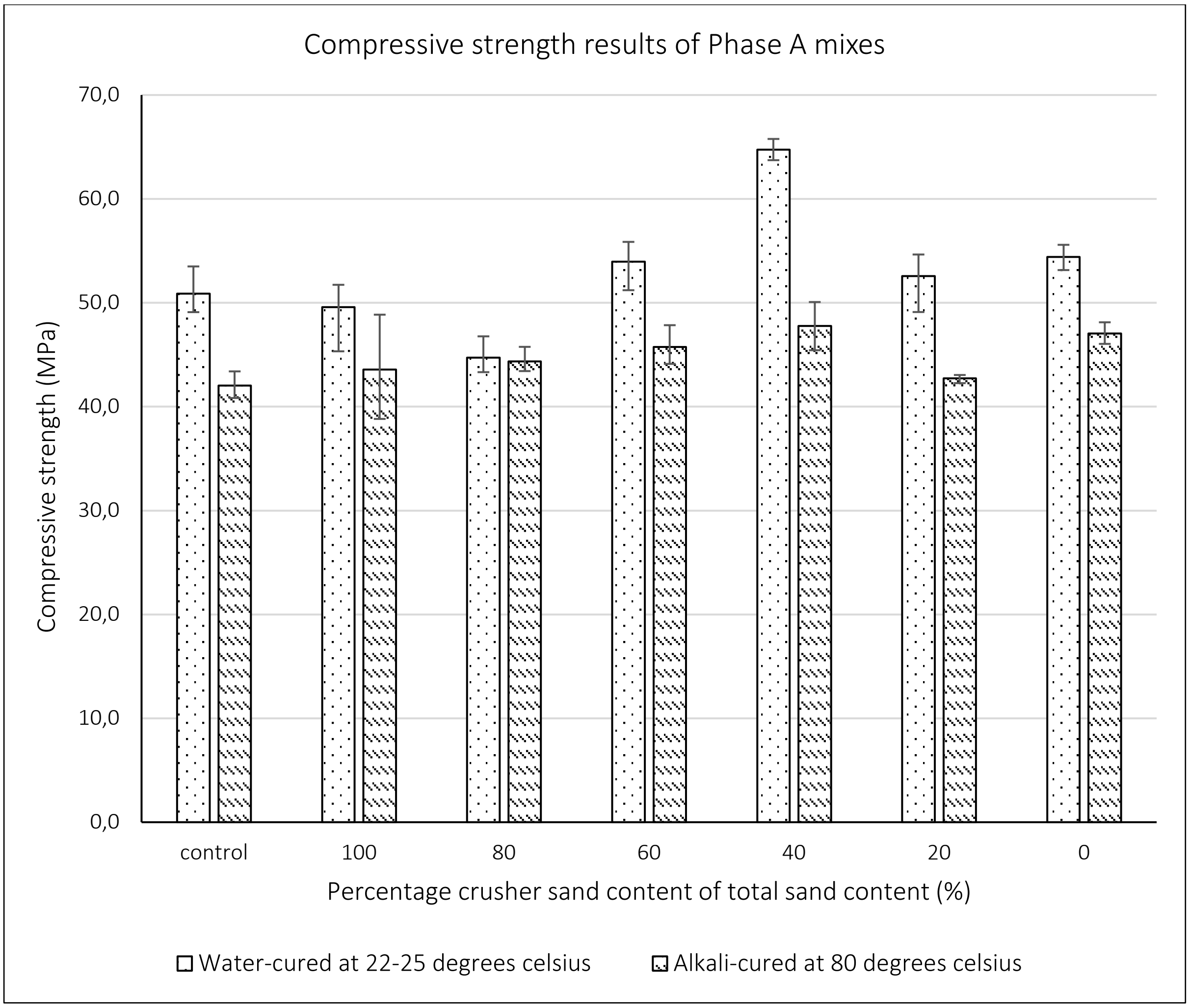

*Figure 4-7: Compressive strength results of Phase A preliminary mixes*

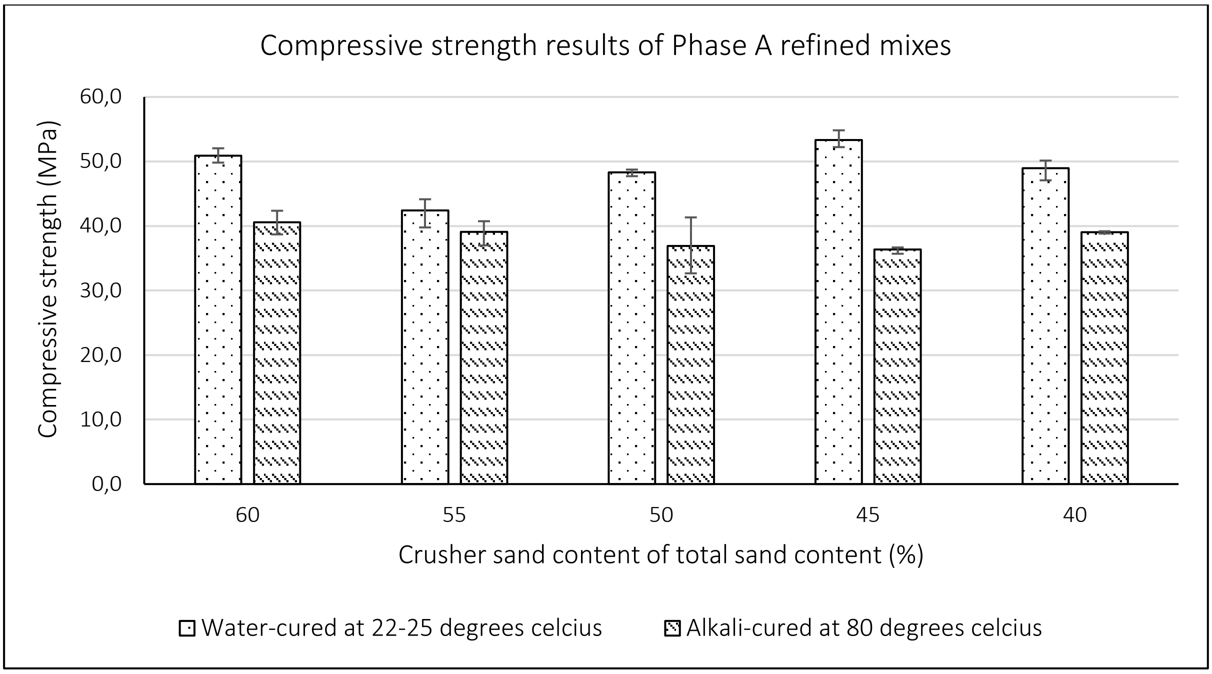

*Figure 4-8: Compressive strength results of Phase A refined mixes*

### 4.3.2 Influence of cement extenders and fillers

Phase B of the research involved the substitution of cement extenders at different levels. In total, 7 mixes were investigated of which 6 contained either fly ash or corex slag, with one being the control with no cement extenders. Figure 4-9 illustrates the compressive strength of the mixes in Phase B. Phase C entailed the substitution of a limestone filler at the same replacement levels as the SCMs. Figure 4-10 depicts the compressive strength of the mixes in Phase C. The error bars indicate the maximum and minimum values obtained for each mix. Detailed results of these tests can be found in Appendix F2.

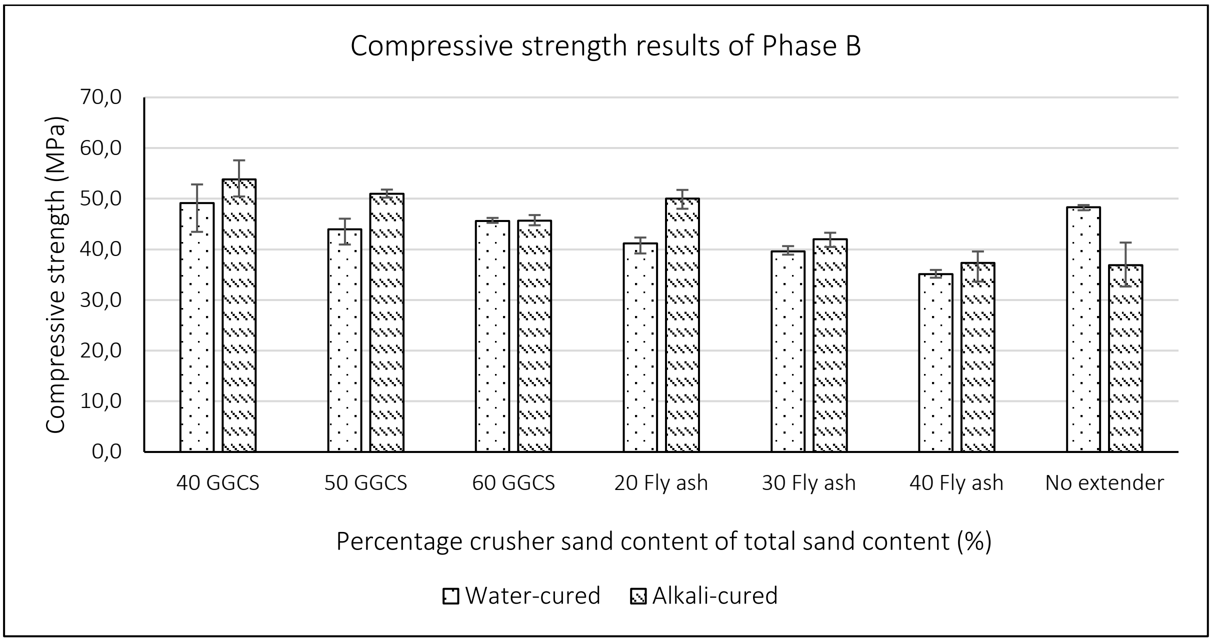

*Figure 4-9: Compressive strength test results of Phase B mixes*

The different mixes were subjected to two curing conditions as depicted in Figure 4-9, i.e. water-curing at 22-25 ° C, and alkali-curing in a 1M NaOH at 80 ° C. Regarding the water-cured specimens, the inclusion of cement extenders into the mix causes a decrease in the compressive strength of all the concrete mixes, relative to the control, with the exception of the mix containing 40% GGCS. The latter had an average compressive strength of 49.1 MPa compared to the 48.3 MPa of the control mix. However, t-test performed showed no statistical significant difference between the two mixes at a confidence level of 95%. The reduction in strength, however, in the other mixes can be attributed to a delayed rate of strength development for water-cured specimens. The higher the fly ash or GGCS content, the slower is the rate of strength development (Vollpracht et al. 2018).

Considering the alkali-cured specimens, unlike the control, the alkali-cured specimens of the mixes containing cement extenders had an increase in compressive strength relative to their water-cured counterpart. As described earlier in Section 4.2.2, the addition of cement extenders controlled the ASR expansion to acceptable amounts. It therefore appears that, in consequence, the mechanical properties of those mixes were not adversely affected. This is true despite some internal microcracking damage to these concretes as discussed further in Section 4.4.2 below. The increase in compressive strength in these specimens can therefore be attributed to the stage of strength development. The alkali-cured specimens being stored at 80℃ are at a more advanced stage of strength development than the water-cured specimens as higher temperatures accelerate the rate of reaction. With regards to the alkali-cured specimen of the control mix, the mixes containing cement extenders exhibited higher compressive strength. This would be attributed to the reduction in the extent of cracking and consequent internal damage, as shown in Section 4.4.2, associated with the inclusion of cement extenders.

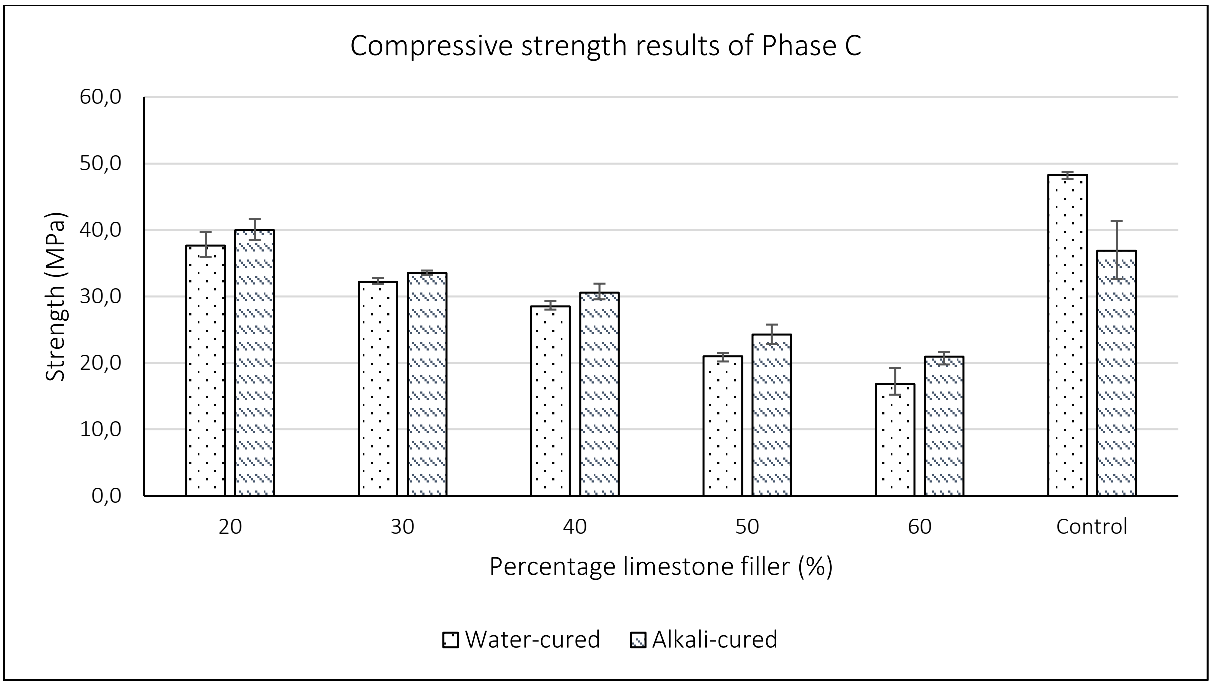

*Figure 4-10: Compressive strength test results of Phase C mixes*

From Figure 4-10, it is evident that the addition of limestone filler results in reduction in the compressive strength of the concrete. Higher replacement levels of the limestone led to a greater reduction in strength. Despite being relatively 'inert', limestone filler does impact the hydration process of cement. It reacts primarily with alumina to form carboaluminate. These carboaluminate hydrates contribute to strength enhancement and porosity reduction through pore filling. However, the percentage of alumina in Portland cement is relatively low and once used up, the excess limestone does not contribute to any reaction products (Rameziananpour & Hooton 2014). Ramezanianpour & Hooton (2014) demonstrated that a limestone filler of up to around 8% is beneficial in terms of strength and porosity for the cement utilised in their study. In Figure 4-10, the minimum replacement level was 20%, in addition to the 9% already incorporated in the CEM II A/L 52.5N. Consequently, the decrease in strength observed was expected as less cement particles are involved in the hydration process with the same amount of water available, thereby increasing porosity.

Regarding the alkali-cured specimens, the results are indeed very interesting. Despite the limestone being relatively 'inert', concretes using limestone filler showed improved strengths compared to their controls, despite internal damage due to AAR cracking (see Section 4.4.2). Also, the limestone filler was moderately effective in mitigating ASR as described in Section

4.2.3. Certainly, the higher temperatures to which the alkali-cured specimens were subjected, increased the rate of hydration reaction of the cement particles. However, the limestone filler also seems to have the ability to mitigate internal damage to the specimens, thus not adversely reducing strength. This clearly is a phenomenon that bears further investigation, scone the mechanism is not immediately apparent.

Relative to the mixes containing the cement extenders, the mixes with limestone filler at the same replacement level resulted in lower compressive strength. This is attributed to the products of the pozzolanic reactions which contributed to the matrix and pore refinement of the matrix.

## 4.4 Subsidiary test results

### 4.4.1 Light microscopy

The experimentation performed by Guthrie and Carey (1997) demonstrated that the two indicators in the dual-staining test method sorb the gel products associated with ASR. The sodium cobaltinitrite indicator is absorbed by potassium rich ASR gels to form a yellow precipitate. It is to be noted that K ions is present in both non-swelling and swelling gel products of ASR and therefore these could not be identified separately using this test. Nevertheless, both are required for the reaction to cause expansion as discussed in Section 2.3.2. Guthrie and Carey (1997) reported that the amount of potassium found in typical CSH is deemed to be minor and does not affect the results of this test. The second indicator, rhodamine B, is reported to sorb into Ca-rich but K-poor ASR gels, which are probably derived from the leaching of alkalis from K-rich gel products, to form a pink colouration. It is also reported by Guthrie and Carey (1997) to not be absorbed by CSH but may be absorbed by $CaCO_3$. Figure 4-11 depicts the results of this test on the critical mixes.

Slices of concrete samples were cut from the middle of cube specimens identified as critical mixes in Section 3.3. The dual-staining method was applied to the slices as described in Section 3.3.1. The results of the test are shown in Figure 4-11.

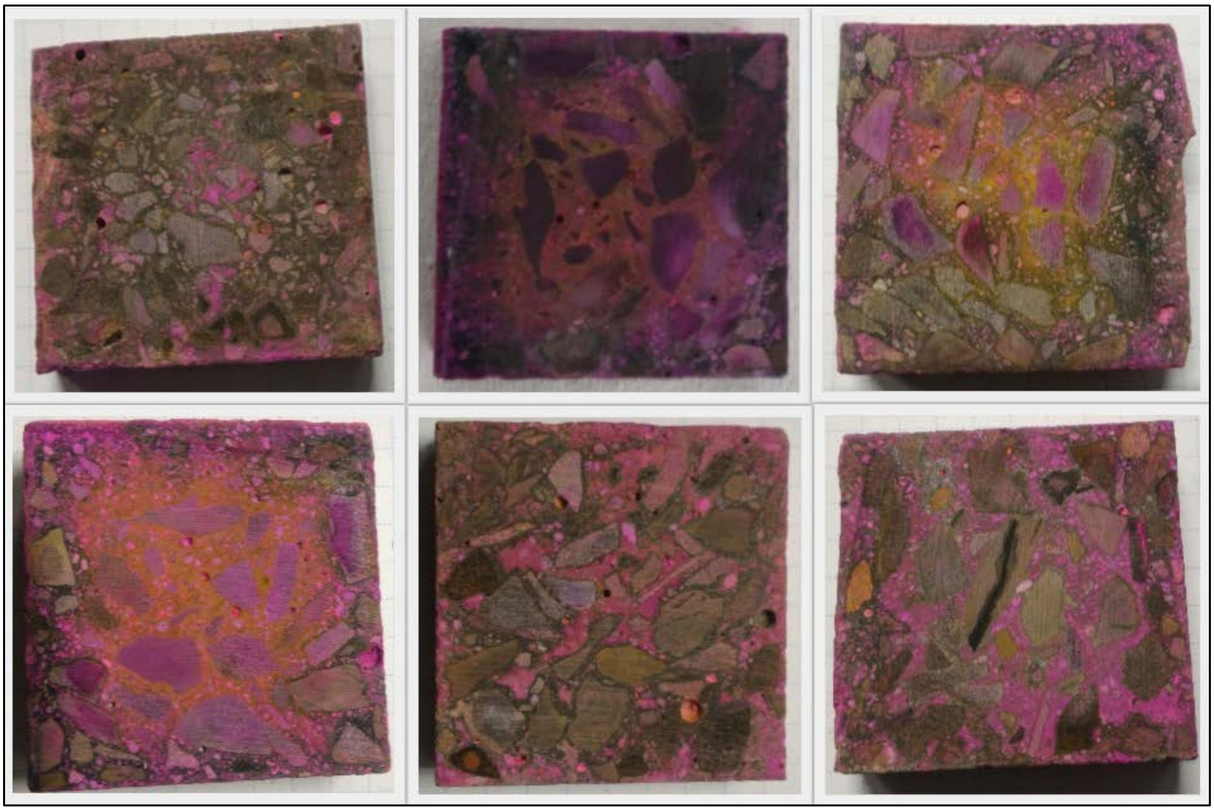

*Figure 4-11: Dual-staining results of critical mixes (Top left to top right: Mix A0, A5 & B2; Bottom left to right: Mix B4, C2 & C4)*

Based on Figure 4-11, the yellow staining is more prominent in mix B2 and B5 which contain 50% GGCS and 20% fly ash by weight of binder respectively. These specimens were stained pink around the edges only. It is therefore a possibility that the potassium in the gel products around the edges had leached out of the specimens. Mix A0, being the control mortar designed as per AAR-2 specifications, and Mix A5, containing only cement as binder and 50% crusher sand in its total sand blend, were moderately stained in yellow with some pink patches. These results are ambiguous as these two mixes experienced the most expansion in the AMBT test and as such were expected to be heavily stained. The inhomogeneous nature of concrete may be a cause of these results. Mix C1 and C4 containing 20% and 40% limestone filler respectively were mostly stained pink with only a thin rim of yellow stain around the aggregates. This could be attributed to the fact that those mixes contained a higher Ca content or that the rhodamine B solution was absorbed by the residual $CaCO_3$ in the paste. From the small sample size tested, it was not possible to quantitatively express the coloration observed with the extent of expansion.

### 4.4.2 Electron microscopy

As described in Section 3.4.2, an electron microscope was used to observe, qualitatively, the crack patterns in the critical mixes identified In Section 0. Two samples were taken from each mix; one close to the surface of the specimen and one in the centre. In general, it was observed that the surface samples were more damaged in terms of crack frequency and crack width than the middle samples. The samples were stored in an alkaline solution and as such there was a greater supply of alkalis and moisture in the surface region of the specimens relative to the deeper region. Figure 4-12 to Figure 4-17 depict the crack patterns observed in each mix.

From Figure 4-12 and Figure 4-13, the control, designed to the standard specifications of the AAR-2, and mix A5, containing 50% crusher sand in the total sand blend, were heavily cracked in both the matrix and the aggregates. This agrees with the AMBT expansion result, whereby the two mixes had the highest expansion among the critical mixes. Cracks of approximately 5-20μm were recurrent. The most deterioration was observed in the interfacial zone between the paste and the aggregates. This cracking could have been exacerbated by the sample preparation technique employed which required polishing of the samples using a 0.25 μm grit. Wider cracks of approximately 10-50 μm were recurrent in both the paste and the aggregates. The samples were stored in an alkaline solution and as such there was a greater supply of alkalis and moisture in the surface region of the specimens relative to the deeper region.

Figure 4-14 and Figure 4-15 illustrate the cracking observed in the mix B2, containing 50% GGCS by weight of binder, and mix B4, containing 20% fly ash by weight of binder. The electron micrographs of the two samples did present cracking in the range of 5-20 μm but it was scarcer relative to the control mix and mix A5. The paste in general was observed to have less micro-cracking than mix A0 or mix A5. The interfacial zone between the aggregates and the paste did show some parallel cracking, with respect to the aggregate surface, but perpendicular cracking, relative to the surface of the aggregate, was insignificant with regard to the cracking observed in the control mix. It was also observed that in general, mix B2, containing GGCS, was slightly more cracked than mix B4, containing fly ash.

Figure 4-16 and Figure 4-17 depicted the electron micrograph of mix C1, containing 20% limestone filler by weight of binder, and mix C4, containing 40% limestone filler by weight of binder. The electron microscope examination of these samples revealed some major localised cracking, especially in the paste, of approximately 50 μm in width. This is probably due to the lower CSH content in those mixes, as a result of substituting cement with limestone, which facilitated crack opening and propagation. However, the density of cracks in the matrix and aggregates were still less than the control mix and mix A5. It is also to be noted that mix C1 had wider and more cracking than mix C4. This corresponds to the AMBT test results whereby mix C1 did experience a higher expansion than mix C4.

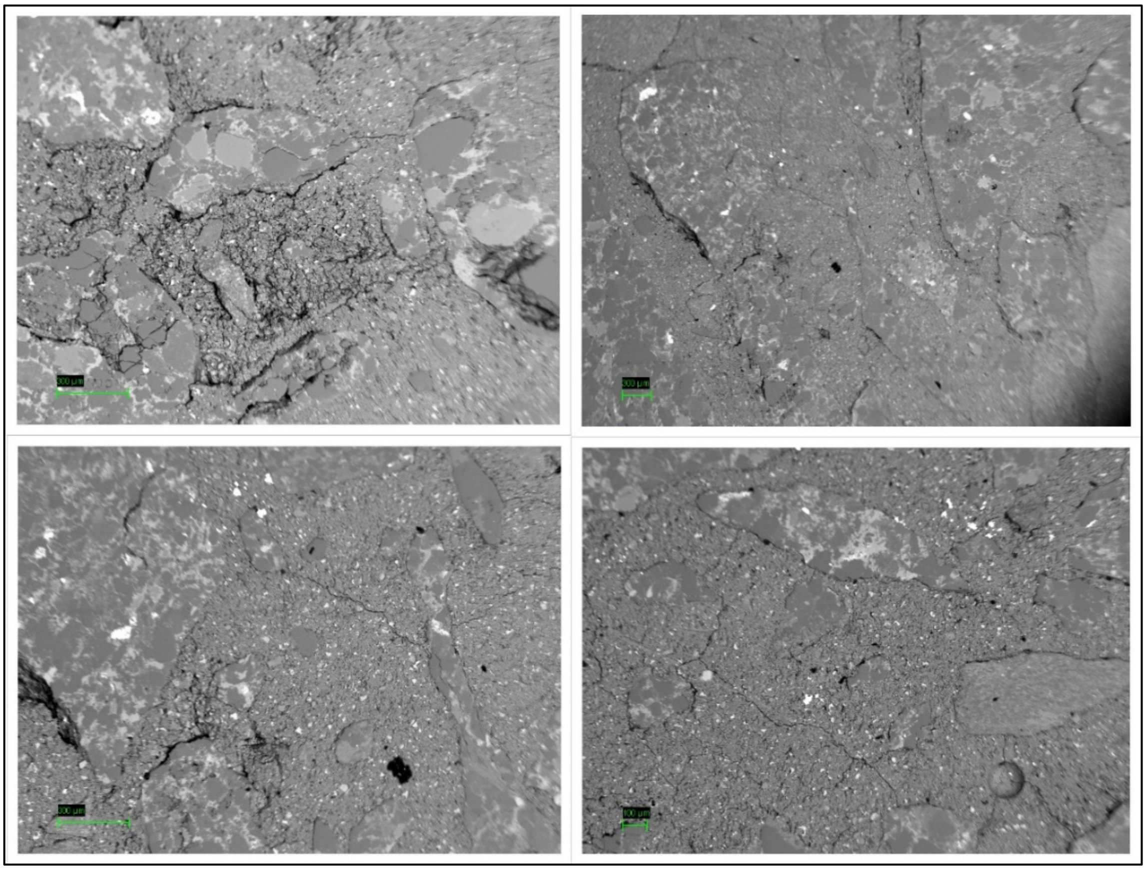

*Figure 4-12: Mix A0 (top: surface sample, bottom: middle sample) *bottom right scale bar is 100µm, remaining is 300µm*

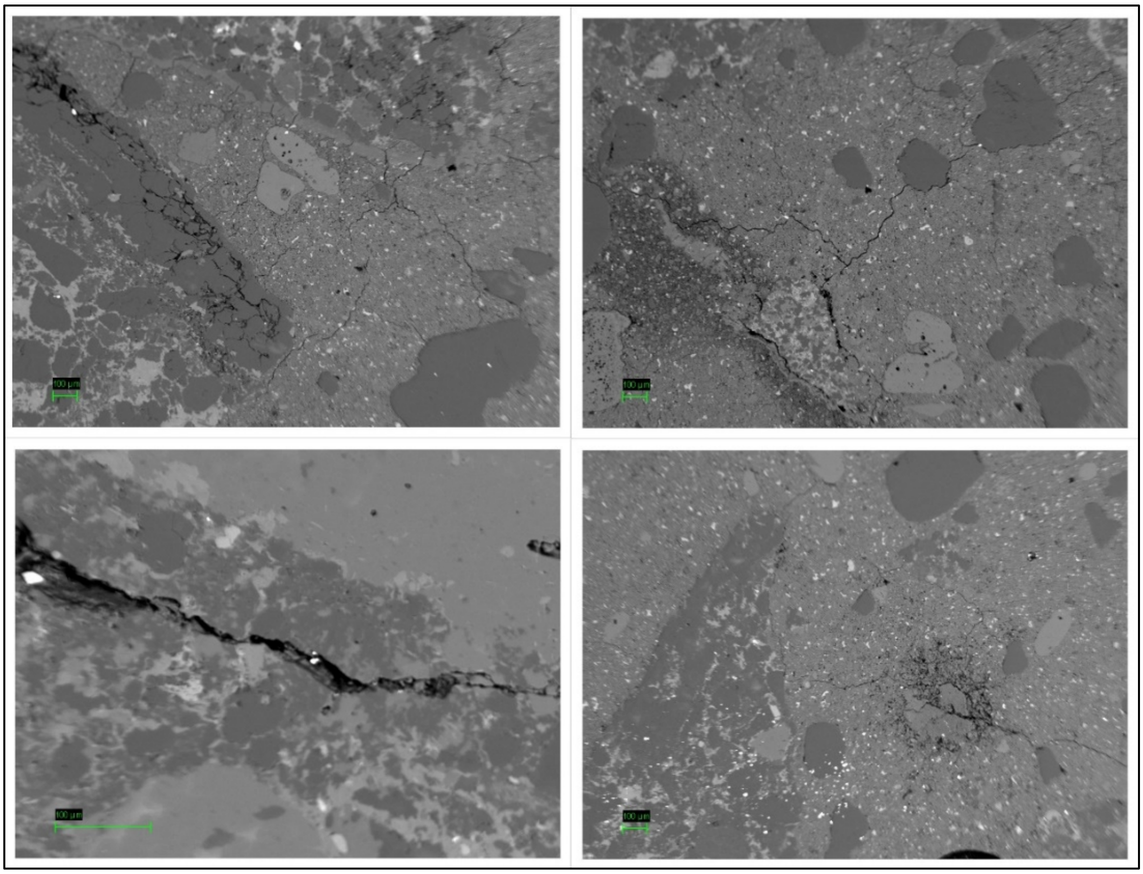

*Figure 4-13: Mix A5 (top: surface sample, bottom: middle sample) *all scale bars are 100µm*

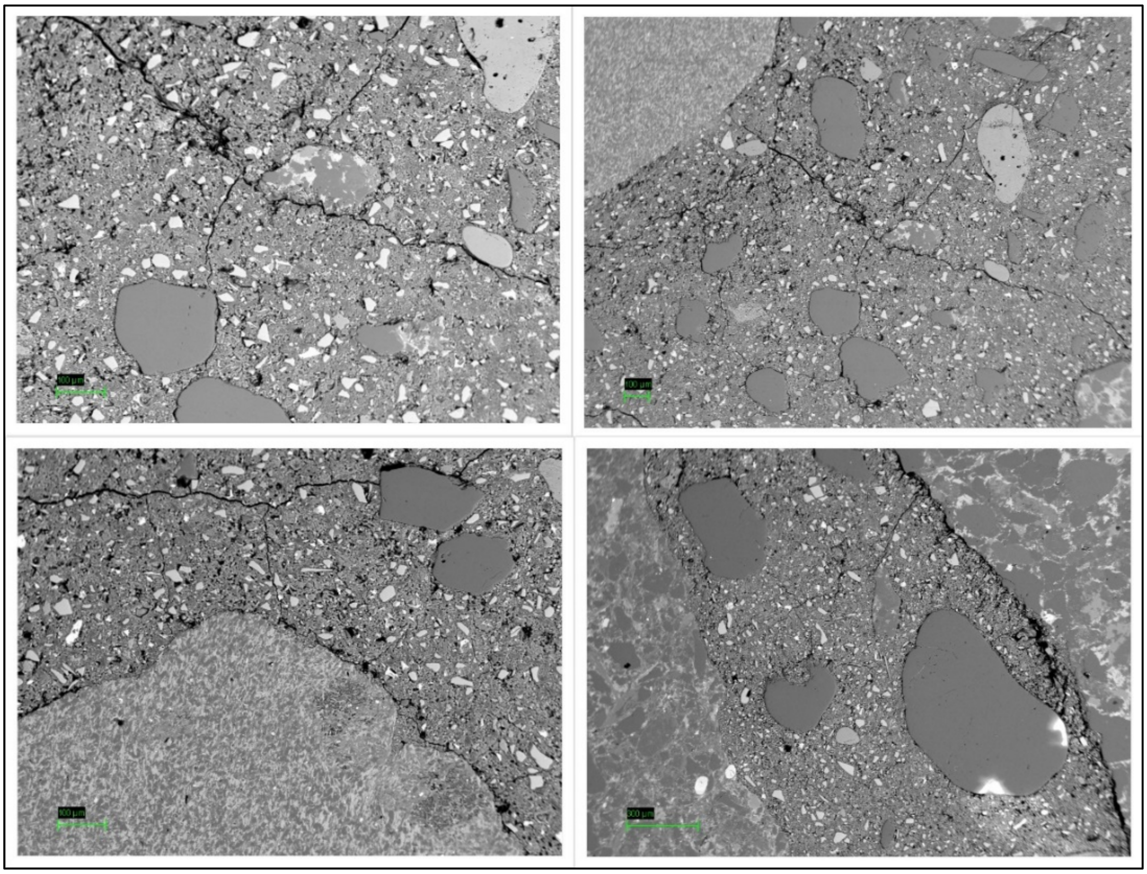

*Figure 4-14: Mix B2 (top: surface sample, bottom: middle sample) *bottom right scale bar is 30µm, remaining is 100µm*

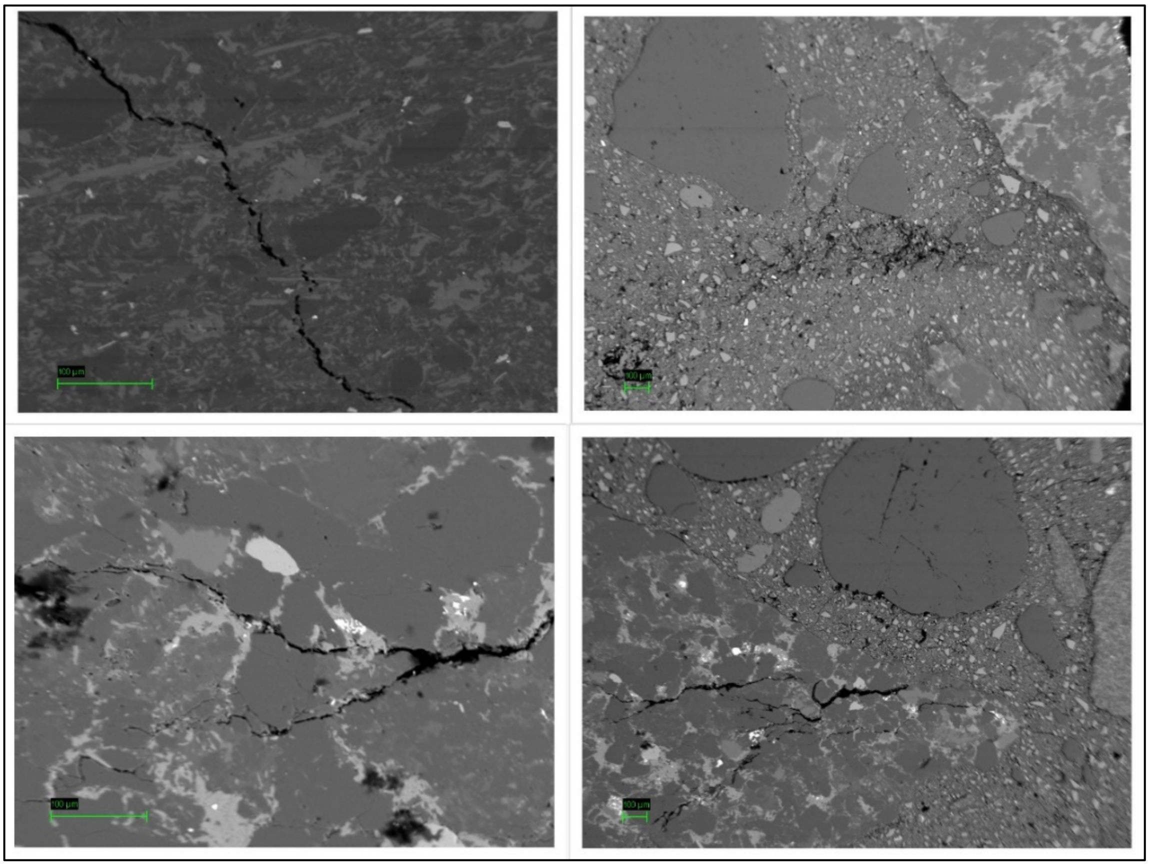

*Figure 4-15: Mix B4 (top: surface sample, bottom: middle sample) *all scale bars are 100µm*

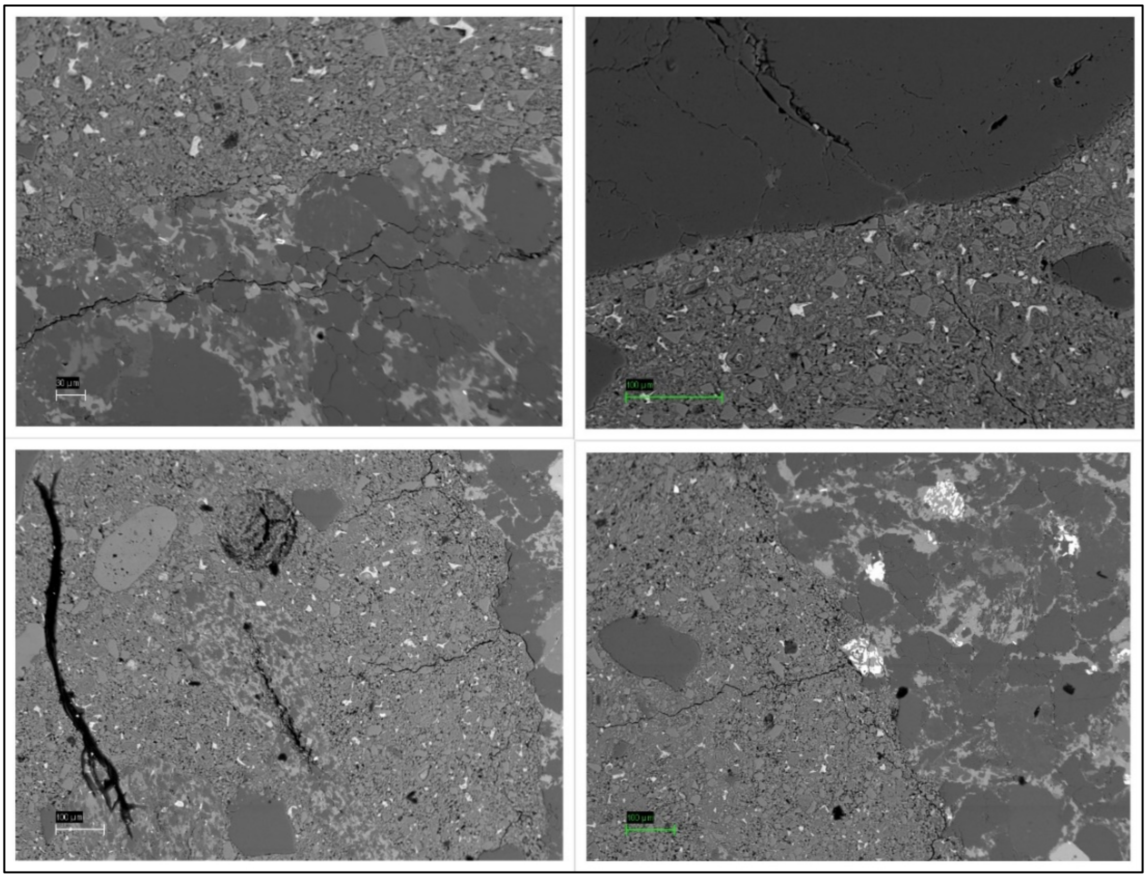

*Figure 4-16: Mix C1 (top: surface sample, bottom: middle sample) *top left scale bar is 30µm, remaining are 100µm*

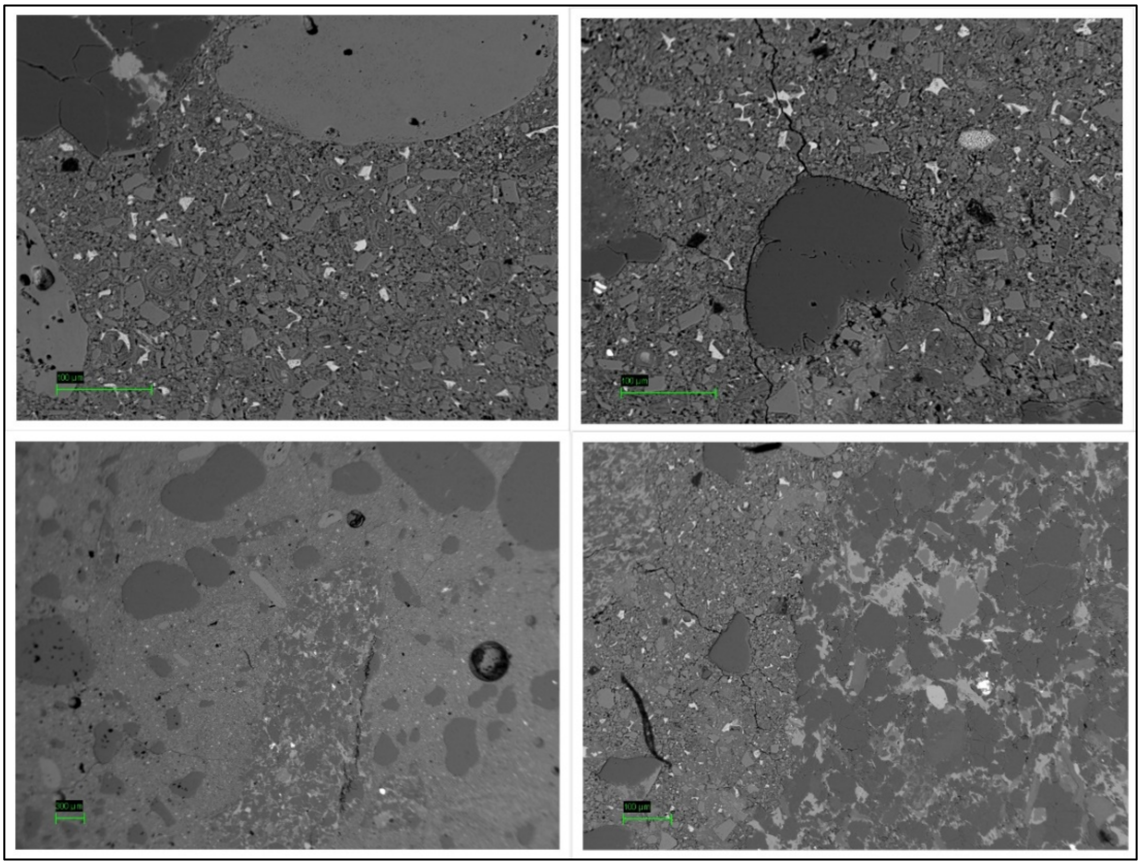

*Figure 4-17: Mix C4 (top: surface sample, bottom: middle sample) *top left scale bar is 300µm, remaining are 100µm*

Regarding the grey-scaling in an electron micrograph, the denser materials appear brighter while the less dense ones appear darker. Looking at Figure 4-12 to Figure 4-17, lighter, i.e. dense, angular particles are seen dispersed in the matrix. These could be unhydrated cement particles or agglomerates of cement or cement extenders as these are generally denser than the hydrated cement products. Trtik et al. (2013) showed that the approximate density of epoxy-impregnated (from the sample preparation for electron microscopy) calcium silicate hydrates is about 1.63 g/cm$^3$ while the unhydrated clinker residue is about 3.21 g/cm$^3$ for the material used in his research. Grieve (2009) also reported that a unit volume of cement generally hydrates to a relative volume of 2.25. Additionally, irregular bright white spots of different sizes can be seen dispersed randomly in both the matrix and aggregates. EDS analysis of these spots showed dense elements such as tin, titanium or tellurium which is known to not be present in concrete. Therefore, the occurrence of such spots is rather indeterminate.

### 4.4.3 EDS

The SEM-EDS, scanning electron microscopy – energy dispersive spectroscopy, was performed on the critical mixes identified in Section 0. These mixes were cured in the alkaline solution, 1M NaOH, for 16 days. Additionally, a water-cured specimen of mix A5, containing 50% crusher sand in the total sand blend, was also analysed for comparative purposes. The EDS was carried out at a magnification of 503×, by pointing the analyser at a single point to analyse the chemical composition of the material at this point. The aim of this secondary test was to attempt to analyse the chemical composition of the gel products in the different mixes. As such, cracks were chosen as points of interest in this test since these would normally be filled with ASR gels in the deteriorated specimens. An average of 3 different points was taken for each mix to calculate the results depicted in Table 4-1. The normalised weight is used to eliminate background noise in the testing process. The test was used as an indication test only, and if conclusive results are required, a much larger set of results would be needed. It is also to be noted that values below 1% should be analysed cautiously as it could be an inaccuracy in the testing regime.

*Table 4-1: EDS results of the critical mixes*

| Mix | EDS results (norm wt %) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Na | | K | | Ca | | Al | | Si | | S | |
| | Avg | std.dev | Avg | std.dev | Avg | std.dev | Avg | std.dev | Avg | std.dev | Avg | std.dev |
| A5 | 1,85 | 0,92 | 1,31 | 1,72 | 20,78 | 14,66 | 3,11 | 2,95 | 8,51 | 4,67 | 0,33 | 0,08 |
| A5-water | 1,26 | 0,30 | 0,62 | 0,23 | 33,66 | 5,58 | 1,49 | 0,31 | 4,95 | 3,89 | 0,45 | 0,41 |
| A0-control | 2,03 | 1,40 | 0,75 | 0,77 | 17,57 | 14,45 | 3,85 | 2,27 | 9,27 | 5,58 | 0,36 | 0,45 |
| B2 | 0,62 | 0,36 | 2,99 | 4,27 | 15,41 | 13,25 | 8,20 | 5,61 | 11,61 | 4,56 | 0,47 | 0,42 |
| B4 | 1,61 | 1,75 | 0,92 | 0,52 | 13,51 | 20,97 | 3,29 | 1,69 | 10,01 | 3,30 | 0,06 | 0,10 |
| C1 | 1,87 | 0,74 | 0,86 | 0,53 | 14,10 | 21,58 | 1,93 | 1,88 | 35,65 | 11,37 | 0,00 | 0,00 |
| C4 | 1,40 | 1,43 | 0,22 | 0,04 | 39,50 | 9,27 | 1,04 | 0,15 | 9,06 | 2,92 | 0,00 | 0,00 |

The results of the EDS test were difficult to interpret, and generally not conclusive. Certain trends such as the higher alkali level in mix A5 when stored in an alkaline solution compared to being stored in water or a higher calcium content for mix C4, containing 50% limestone, versus mix C1, containing 20% limestone are clearly evident. However, other results such as the marginally higher silica level in mix C1 or the increased calcium content in mix A5 when stored in water versus stored in alkaline solution cannot be conclusively quantified and explained. It is also to be noted that the test was dependent on where the analyser was pointed. It is therefore recommended that an elemental mapping of the sample be performed rather than point analysis. If only cracks are to be analysed, a much larger set of data would be required per sample to provide reliable results.

### 4.4.4 Pore expression

As described in Section 3.4.3, a pore expression and subsequent analysis of the pore solution by ICP was carried out on the mixes described in Table 4-2. Unfortunately, Mixes B2 and B4 were not analysed in this test as the pore expression yielded too little solution for these mixes. The results are illustrated below. Note that the ICP-OES has a limit of quantification of 200 ppb (i.e. 200 µg/L). Results are thus reported as <1.00 ppm to compensate for dilution factors. Raw data of the ICP-OES test are provided in Appendix G2.

*Table 4-2: ICP-OES results*

| Mix No | ICP-OES results (ppm or mg/L) | | | | ICP-OES results (mmol/L) | | | |
|---|---|---|---|---|---|---|---|---|
| | Na | K | Ca | Al | Na | K | Ca | Al |
| A0 | 1803,80 | 1379,31 | 2,38 | 1,04 | 78,460 | 35,276 | 0,059 | 0,039 |
| A5 | 1355,81 | 1112,75 | 1,45 | <1.00 | 58,974 | 28,459 | 0,036 | <0,037 |
| C1 | 1058,00 | 968,56 | 1,16 | 5,67 | 46,020 | 24,771 | 0,029 | 0,210 |
| C4 | 971,88 | 994,19 | <1.00 | <1.00 | 42,274 | 25,427 | <0,025 | <0,037 |

The calcium and aluminium content in all the mixes are insignificant relative to the sodium and potassium. It was found that mix A0 and mix A5 have significantly different concentrations of sodium and potassium ion in their respective pore solution, despite the fact that they both contain the same amount of cement. This may be due to the different extent of expansion occurring in the mixes at the time of testing. From the results, the sodium and potassium content of mix A5, having same mix composition as C1 and C4 with the exception of having no extender, was higher than mix C1 and C4, containing 20% and 50% limestone filler respectively. This is due to alkali dilution as the cement is partly substituted with limestone filler, which did not contain significant sodium or potassium. Comparison of the sodium and potassium content measured in the pore solution with their calculated concentration, assuming all Na and K ions in the cement were released, in the respective mix is given in Table 4-3. Refer to Appendix G for the calculation of the total concentration of sodium and potassium in the concrete mixes.

From Table 4-3, both the sodium and potassium content of the concrete mixes, calculated assuming all the alkalis present in the mixes are releasable, are higher than the measured respective concentrations in the pore solution. This is expected as not all the alkalis are releasable in the concrete mixes. Moreover, hydration reaction products also bind some of the sodium and potassium ions. Lastly, the ASR gel products, C-N(K)-S-H and N(K)-S-H also constitute to some degree of the sodium and potassium ions. From a qualitative perspective, mix C4, containing 50% limestone in the total binder content, had a smaller difference between its calculated [Na] and [K] with respect to its measured concentrations than mix C1, containing C1. This links with the observation in Section 4.2.3 whereby mix C1 had a higher expansion than mix C4, i.e. more ASR gel products were produced.

*Table 4-3: Concentration of Na and K in pore solution and total concentration in mix*

| Mix No | Mix composition (mg/L) | | ICP-OES results, mg/L | | Difference | | Ratio | |
|---|---|---|---|---|---|---|---|---|
| | Na | K | Na | K | Na | K | Mix [Na]/ ICP [Na] | Mix [K]/ ICP [K] |
| A0 | 2466,77 | 3484,65 | 1803,80 | 1379,31 | 662,97 | 2105,34 | 1,37 | 1,66 |
| A5 | 2472,51 | 3484,65 | 1355,81 | 1112,75 | 1116,70 | 2371,90 | 1,82 | 1,47 |
| C1 | 1962,90 | 2761,71 | 1058,00 | 968,56 | 904,90 | 1793,15 | 1,86 | 1,54 |
| C4 | 1217,24 | 1709,39 | 971,88 | 994,19 | 245,36 | 715,20 | 1,25 | 2,39 |

However, quantifying the different mechanisms through which the reduction may have occurred was outside the scope of this research. It is therefore not possible to derive conclusions based on the limited results obtained and further testing with a greater sample size should be carried out.

## 4.5 Long term performance test

Long term performance testing was performed on as described in Section 3.5. Five mixes as described in Section **Error! Reference source not found.** were designed and tested.

### 4.5.1 RILEM AAR-4

The RILEM AAR-4 was used as an accelerated performance test with the specimens being stored over a water bath at 60˚C. Readings were taken at 5, 8 and 15 weeks of age from the day of casting. The test is normally run for 20 weeks, however due to the time constraint of this research, those results were unavailable at the time of writing. The preliminary results of this test at 15 weeks of age are illustrated in Figure 4-18. The error bars on the figure illustrates the maximum and minimum expansion observed for each mix. Detailed results of the test can be found in Appendix H.

As can be seen from Figure 4-18, all the specimens tested had values of expansion in the negative range, which implies that the specimens underwent shrinkage. The only mix which experienced a positive expansion in 1 of its 3 specimens was D3, containing a boosted alkali content using NaOH solution. As aforementioned, for ASR to take place, 3 conditions, namely sufficient alkalis, sufficient moisture and reactive aggregates need to be present at the same time. In this stage of testing, the reactive aggregates were provided by the greywacke aggregate which as shown in Section 4.2.1 is highly reactive. The moisture was provided by suspending the specimens over a water bath, which was regularly replenished to a height of 35mm. Nevertheless, the ingress of water in the specimens was not quantified and it is uncertain whether the moisture level in the specimens was sufficient to sustain the ASR expansion. Lastly the alkali levels in the mixes could be a reason for the negative expansion. The cement used, CEM II A/L 52.5N has a sodium equivalent of 0.7. In Chapter 2, it was discussed that a sodium equivalent of greater than 0.6 is required for the reaction. However, 0.7 $Na_2O$ eq is relatively close to that limit and ASR gel formation may have been stifled by a lack of releasable alkalis in the pore solution. This would explain why mix D3, which had a $Na_2O$ eq of 1.0, experienced the least shrinkage and had a result in the positive expansion result on one of its specimen. ICP analysis of the water bath (refer to Appendix G2) showed that negligible alkali was leached out of the specimens.

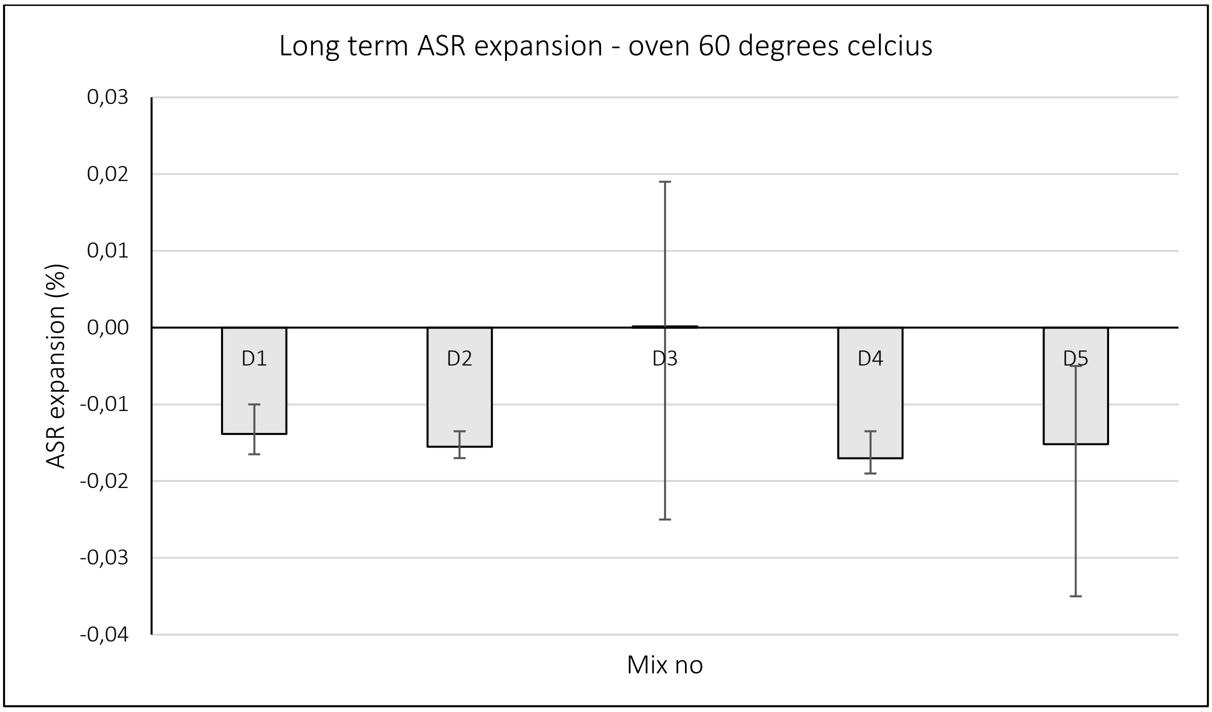

*Figure 4-18: Preliminary results of the RILEM AAR-4 (15 weeks data)*

It is to be noted that the results provided herewith are only preliminary and that the test will be continued beyond the period of this thesis for long-term results.

### 4.5.2 Field testing

As described in Section 3.4, 100×100×200 mm specimens were cast and exposed to the environment. Measurements of expansion were taken in-situ, at the storage spot, at intervals of 5, 8 and 15 weeks. Results were also taken in a controlled environment, with temperature at 21˚C and humidity level of 52% for the 8 weeks results. A t-test performed between these measurements and ones taken in-situ showed no statistical difference at 95% confidence level. Refer to Appendix H for t-test analysis. The results of the expansion at 15 weeks are shown in Figure 4-19. The errors bars illustrate the maximum and minimum expansion noted for each mix. Detailed results can be found in Appendix H.

As can be seen from Figure 4-19, the results of the field testing at 15 weeks demonstrated the all the mixes experienced shrinkage, implying that ASR expansion in those specimens was insignificant. Comparing mix D3 from Figure 4-19 and Figure 4-18, whereby the specimens were stored in the oven, in the field testing stage the same mix experienced a relatively higher shrinkage. As explained earlier, the mix contained reactive aggregate and the alkali content of the mix was boosted to 1.0 $Na_2O$ eq, which is above the 0.6 limit, sufficient for ASR expansion to start. However, the moisture conditions experienced in-situ over the period of testing (Humidity levels; November 2017 67%, December 2017 63% and January 2018 68%) was below the 85% humidity required for the reaction to take place. Consequently, loss of moisture from the concrete resulted in drying shrinkage which would explain the results illustrated in Figure 4-19.

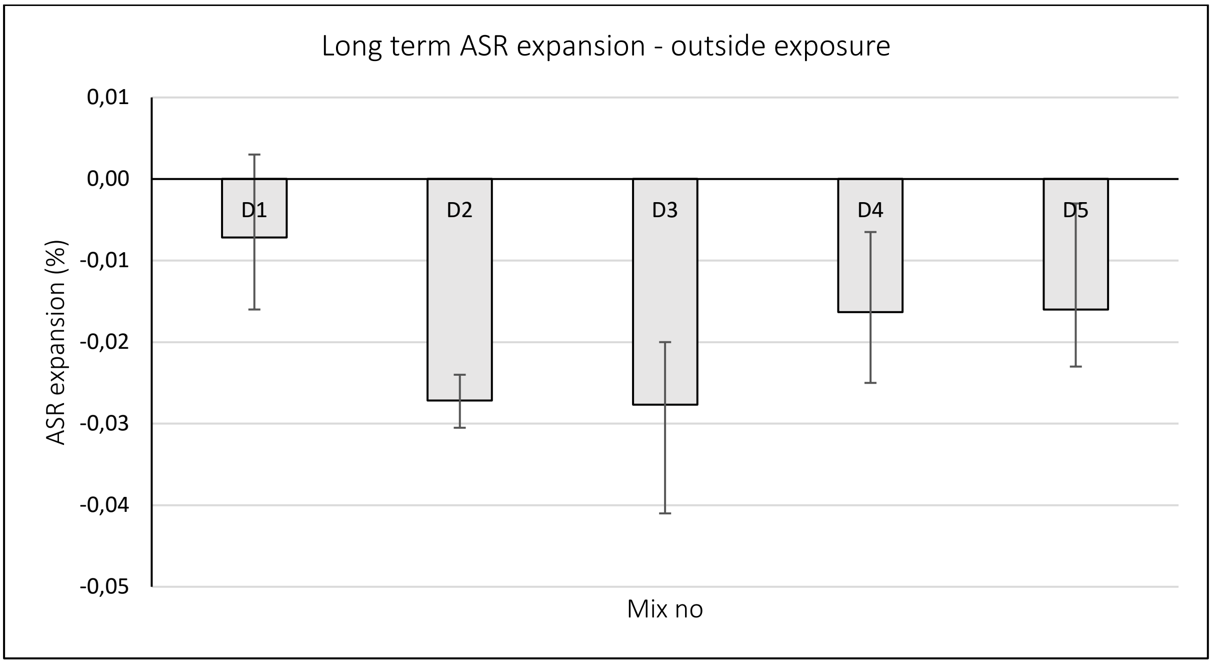

*Figure 4-19: Preliminary results of long term field testing (15 weeks data)*

From Figure 4-19, the results of the field testing at 15 weeks demonstrated the all the mixes experienced shrinkage, implying that ASR expansion in those specimens was insignificant. Comparing mix D3 from Figure 4-19 and Figure 4-18, whereby the specimens were stored in the oven, in the field testing stage the same mix experienced a relatively higher shrinkage. As explained earlier, the mix contained reactive aggregate and the alkali content of the mix was boosted to 1.0 $Na_2O$ eq, which is above the 0.6 limit, sufficient for ASR expansion to start. However, the moisture conditions experienced in-situ over the period of testing (Humidity levels; November 2017 67%, December 2017 63% and January 2018 68%) was below the 85% humidity required for the reaction to take place. Consequently, loss of moisture from the concrete resulted in drying shrinkage which would explain the results illustrated in Figure 4-19.

It is to be noted that field testing is normally carried out over long periods of time, generally about 2 years minimum. As such, significant expansion was not yet expected at this stage of testing. Measurements of expansion of these samples will be continued beyond the period of this research.

# 5 Conclusions and recommendations

## 5.1 Overview of chapter 5

This chapter summarises the main findings and discussion presented in Chapter 4 and provides the main conclusions drawn and recommendations made based on the results. A summary of the influence of reactive greywacke crusher sand on ASR expansion is provided in Section 5.2. Section 5.3 then details the findings made when employing cement extenders to mitigate the expansion due to ASR. This section also discusses the inclusion of limestone filler to explain the difference between the mitigation mechanisms of cement extenders. Additional findings made through this investigation are discussed in Section 5.4. Lastly, a summary of the conclusions drawn from the investigation as well as recommendations for future studies are provided in Section 5.5 and 5.6 respectively.

## 5.2 Influence of reactive greywacke fine aggregate in concrete

The introduction of reactive greywacke coarse and fine aggregate in the mix composition was observed to influence both the extent of ASR expansion and compressive strength of the mixes tested in phase A. The introduction of 9.5mm greywacke coarse aggregates and use of different combinations of reactive greywacke coarse and fine aggregates alongside non-reactive Philippi dune sand are discussed in the following paragraphs. Note that the results from this work were achieved by modifying the AAR-2 AMBT test, and as such results should be reviewed from a qualitative as well as a quantitative perspective.

The AAR-2 standardised mix, which acted as the control in Phase A, contained only reactive greywacke fine aggregate in the mix, graded to the specifications of the standard. Comparatively mix A1, containing 60% greywacke coarse aggregate and 40% greywacke fine aggregate, also had the same amount of reactive aggregate on a weight basis. From the results obtained, it was found that the extent of expansion for the two mixes. 0.20% and 0.15% respectively, were significantly different based on a t-test with confidence level of 95%. However, this is from an analytical point of view. In practice, the AMBT test is used as an indicator test to mainly distinguish between non-reactive and reactive aggregates. In this particular case, despite the 0.05% difference in expansion, both those results would require validation using a more reliable performance test as the expansion would be deemed significant.

Generally, when designing mixes, aggregate grading is one of the most important aspects as it impacts both fresh properties of concrete, in terms of flowability, cohesiveness and bleeding, and hardened properties, in terms of packing density. As such, ‘extreme mixes’ such as one containing only crusher sand which is very angular are rarely used. Common mixes in the Western Cape would be composed of a combination of the angular greywacke crusher sand and rounded Philippi dune sand to balance the fine aggregate grading, usually in a 1:1 ratio. Subsequently, different combinations of greywacke crusher sand and Philippi dune sand in the sand blend were tested while keeping the coarse aggregate, 9.5mm greywacke stone, fixed at 60% of the total aggregate content. It was observed that as the reactive greywacke crusher sand content increased from 0 to 100 percent in the sand blend, there was a gradual increase in expansion up to a peak expansion at around 40-60% crusher sand content, followed by a decrease in expansion beyond that point. This phenomenon would be described as a pessimum proportion effect, whereby at a certain amount of aggregates, the ASR expansion reaches a maximum. However, from an analytical point of view using a t-test at confidence level of 95%, the difference between the results were deemed insignificant. Therefore, it is debatable whether the trend observed should be definitely classified as a pessimum. Since one of the results, for the mix containing 40% crusher sand in the sand blend, had an expansion of 0.21% which classified it as deleteriously reactive, it was deemed reasonable to categorise the trend as a limited pessimum proportion effect. Refinement of the results around the maximum expansion observed did not provide more clarity as all the expansions observed were within 0.02% expansion of each other. However, again from a practical point of view, all the mixes had expansion of around 0.15% upwards in the AMBT indicator test, which would require validation from a performance test. However, the AMBT test seemed capable of detecting relatively small though important differences between the various mixes, and thus proved useful for this study.

The influence of adding reactive crusher sand in concrete mixes on ASR expansion was also investigated in the long-term performance tests, via the AAR-4 and field testing. Mix D1, containing 60% greywacke coarse aggregate and 40% Philippi dune sand, acted as the control, while mix D2 containing 60% greywacke coarse aggregate and a blend of 1:1 greywacke crusher sand and Philippi dune sand in the sand blend, allowed for comparison. However, the results up to the time of writing did not provide a conclusive explanation on this effect as the measurements were still showing apparent shrinkage, indicating that the expansion had not yet started. The measurements of expansion on these long-term specimens will need to be continued beyond the period of this study.

Compressive strength being one of the most common parameters used in assessing concrete quality was also investigated in this study. Two sets of specimens from each mix were subjected to two different curing conditions, namely a water bath at 22-25℃ and an alkaline solution of 1M NaOH at 80℃. The influence of varying crusher sand contents on compressive strength by comparing the water-cured specimens could not be directly identified since several other factors such as packing density and porosity amongst others also affect this property. However, when comparing the results of each mix individually, it is evident that subjecting the mix to an alkaline solution, which promoted ASR gel formation, led to a decrease in compressive strength relative to the water-cured specimens. It was further observed that the greater the expansion, the higher was the reduction in strength. This is attributed to the increased cracking which is associated with a greater amount of ASR gel product formation. The highest reduction in compressive strength observed in this study due to ASR was 26%, with an absolute value of 17 MPa. Generally, when designing mixes for structural purposes, a characteristic strength is determined which is required to sustain the loading on the structure.

For safety purposes, the characteristic strength is factored by 1.64 times the standard deviation, derived from the quality of site control, to achieve an average mix target strength. For example, a good site control would imply a standard deviation of 5 MPa which results in 8.2 MPa increase. The highest reduction in strength obtained in this study was from subjecting the specimens to extreme conditions of alkalinity and temperature. It is not expected to encounter such conditions in practice and as such ASR may be more of a concern to the durability properties of concrete rather than the mechanical aspect.

## 5.3 Influence of cement extenders and limestone filler

Mix A5, containing 60% coarse aggregate and 1:1 ratio of greywacke crusher sand and Philippi dune sand in the sand blend, was chosen as the control for Phase B and Phase C of testing. The mix was modified by substituting cement with cement extenders or limestone filler at different replacement levels. The aim was to investigate the mitigation of ASR as well as the mitigation mechanisms involved when using cement extenders.

Fly ash at replacement levels of 20, 30 and 40 percent and ground granulated corex slag at replacement levels of 40, 50 and 60 percent were employed in this study. It was observed that even at their lowest replacement levels respectively, the cement extenders were effective in reducing the ASR expansion to allowable limits, i.e. below 0.10% expansion, in the modified AMBT test. It was also noted that fly ash was more effective in controlling ASR as a replacement level of 20% fly ash had relatively similar expansions as a mix containing 60% corex slag. Long term testing on the influence on cement extenders did not produce conclusive information within the time period of this research, and will need to be continued beyond this time frame.

The decrease in expansion is associated with two main mechanisms, namely alkali dilution and reaction effects. The substitution of cement extenders with the same amount of nominally ‘inert’ limestone filler demonstrated that there are indeed at least two mechanisms via which cement extenders reduce ASR expansion. Since the limestone filler is relatively ‘unreactive’, the only mechanism through which the decrease in ASR expansion can be associated with is alkali dilution, i.e. a decrease in the total alkali content present in the mix itself. The pore expression results showed this decrease in alkali content when employing limestone filler. Nevertheless, when comparing mixes with the same replacement levels of limestone, fly ash and corex slag, the fly ash and corex slag mixes experienced less expansion than the respective limestone mix. This confirms that there are further reaction mechanisms which take place between the cement extenders and the pore solution of concrete, leading presumably to a greater reduction in ASR gel formation. The inclusion of cement extenders in mixes to combat ASR gel formation is therefore confirmed as a viable option. The quantities of fly ash (20%) or corex slag (40%) required to mitigate ASR are present in certain commercially available cements such as CEM II B-V and CEM III A. It is therefore important to choose the right cement when dealing with aggregates that are reactive with respect to ASR.

Regarding the use of limestone filler, a replacement level of cement with the limestone from 0-50% resulted in a gradual decrease in expansion. However, at replacement level of 60%

by mass limestone in the binder, the expansion measured was higher than that of the mix containing 50% limestone filler. It is still uncertain whether this trend will increase as the limestone filler is further increased and further investigation would be needed. However, from a practical point of view, limestone use in cement does not normally go beyond 40% by weight of binder as mixes exhibit greater porosity and lower strength.

With respect to compressive strength, it was noted that the inclusion of cement extenders decreased the strength relative to the control in the water-cured samples. This is due to a delayed rate in strength development associated with cement extenders. Similarly, addition of limestone filler also decreased the strength due to increased porosity and lower strength of the matrix. However, both the cement extenders and limestone filler did prove to be beneficial in mitigating the reduction in strength when subjected to an alkaline environment. All the mixes, containing cement extenders or limestone filler, measured somewhat higher compressive strengths on the specimens subjected to an alkaline solution of 1M NaOH at 80℃ relative to their specimens subjected to a water bath at 22-25℃. This is associated with the decrease in ASR gel formation as evidenced in the AMBT test as well as an acceleration of hydration due to the higher temperature. Electron micrograph of the samples also showed that the mixes containing cement extenders or limestone filler, experienced less micro-cracking than the mix containing only cement as binder.

## 5.4 Additional findings

Additional findings observed in this research which were not directly related to the influence of reactive greywacke crusher sand or the inclusion of cement extenders and limestone filler are detailed herein.

As described in Chapter 3, modifications had to be made to the AAR-2 standard test to mimic more closely ‘real-life’ concrete mixes. Initially, it was uncertain whether those modifications would negatively impact the results of the AMBT test. As such, expansion measurements using the AMBT test were taken at both 14 days and 28 days. It was observed that the 28 days results for all the AMBT tests followed the same trend as their respective 14 day results. Therefore, it was possible to use the 14 day results of the modified AMBT test on a qualitative basis when analysing the results. It was also observed that the inclusion of coarse aggregate in the concrete mix (to create a ‘micro-concrete’) generally resulted in lower expansion than the mix containing only fine aggregate.

It was also observed that repeatability was a major issue in the AMBT test. The mix containing 40% reactive greywacke crusher sand in the total sand blend was repeated in the refined stage of Phase A. The initial result showed an expansion of 0.21% while the refined result measured only 0.15%. From a statistical point of view, the difference between the two results were not significant. However, from a practical point of view, a difference of 0.05% would be a relatively significant increase in expansion.

With respect to the long-term AAR-4 performance testing, a specimen with cross-section of 100×100 mm was used instead of the standard 75×75 mm as described in the AAR-4 test.

This modification was derived from the Norwegian test method whereby a bigger specimen size is used with the aim of minimising alkali leaching, which is a concern in the AAR-4 test. ICP-OES analysis of the water bath over which the samples were stored showed insignificant alkali leaching from all the specimens tested.

## 5.5 Conclusions

The following conclusions were drawn from the experimental work performed in this work:

1. The concurrent use of reactive coarse aggregate and reactive fine aggregate in the mix does have an impact on ASR expansion measured in the AMBT test, compared to the standard grading specified in the AAR-2 test method. The standardised grading generally results in a higher expansion;
2. The reaction was evident also in the mix containing no reactive greywacke in the sand blend, proving that even 60% reactive coarse aggregate in the total aggregate content, which is a common stone content, is enough to start the reaction;
3. A minor pessimum effect was observed when varying reactive greywacke crusher sand content in the sand blend. This was found to be around the replacement level of 40-60% reactive greywacke crusher sand in the sand blend, which represents common levels in 'real-life' concrete mixes;
4. Expansions measured on all the mixes were below 0.20% except for the mix containing 40% reactive crusher sand. However, the same mix when repeated, as well as mixes with crusher sand levels close to the 40% replacement level, experienced expansions lower than 0.20%. Based on the AAR-2 standard test specifications, the mixes would be classified as 'slowly reactive', deeming them safe for use. Nevertheless, it would be good practice that mixes with results which were above 0.15% are still verified using a performance test to validate their use in 'real-life';
5. Cement extenders used in this study, Class F fly ash and ground granulated corex slag, were effective in mitigating the ASR expansion to negligible amount, i.e. below 0.10% expansion limit;
6. At the same extender proportion, fly ash is more effective at controlling ASR expansion than ground granulated corex slag, with regard to the decrease in expansion;
7. There are at least two mechanisms through which cement extenders mitigate ASR in concrete. The first is alkali dilution, evidenced when the cement extenders were replaced by a nominally 'inert' limestone filler. The second is a reaction mechanism between the cement extenders and the alkalis in the pore solution; and
8. The reaction mechanisms when using cement extenders are more significant in reducing ASR than only the alkali dilution mechanism.

In general, it can be concluded that the partial replacement of natural sand with reactive greywacke crusher sand in a mix already containing the same reactive greywacke coarse aggregate in concrete, would not increase expansions compared to the standard AMBT test whereby purely reactive greywacke is tested. This implies that the measures already prescribed to combat ASR, i.e. the use of 20% fly ash or 40% slag, do not require any change.

## 5.6 Recommendations

This study was performed to provide a qualitative and quantitative look at the influence of adding reactive greywacke fine aggregate in concrete, which also contains the reactive greywacke in coarse aggregate form, with non-reactive dune sand. Modifications made to the AMBT test method implied that quantitative meaning of the results could only be derived in a comparative way for this test. Therefore, the following recommendations are suggested for future research to allow for that, as well as to tackle the hurdles faced in this study.

1. **Long term performance testing**
   Due to the limited period allowed for this study, long term performance testing was only conducted on a select number of mixes and for a limited time. However, these tests are more reliable than the AMBT test when assessing ASR potential and allow for a greater variety of mix compositions and aggregate grading. As such, it is recommended that a performance test such as the RILEM AAR-4 or the Norwegian test is used for future research into the influence of using reactive fine and coarse aggregate in conjunction.
2. **Repeatability of test**
   As evidenced in this research, the AMBT test repeatability was questionable. It is therefore recommended that for future testing, the test is to be performed at least twice for each mix and an average taken as the final result.
3. **Cement extenders and commercial cements**
   This research was limited to the use of either Class F fly ash or corex slag. Other common cement extenders such as condensed silica fume or ground granulated blast furnace slag could also be used in future research to assess which cement extender is more effective in mitigating ASR. Moreover, ternary blends containing more than one cement extender could also be investigated. It is also recommended to assess commercial cements using performance testing.
4. **Crack mapping**
   The microscopical analysis of the samples to comparatively determine the extent of cracking in the different mixes provided in this study was limited. Only one sample from each mix was inspected using the electron microscope. It is therefore recommended that for future work, a greater sample size is used for each mix, with several electron micrographs for each sample, in order to be able to quantitatively analyse the extent and patterns of cracking in the different specimens. Also, optical microscopy might also be used quite adequately for this work.
5. **Elemental mapping**
   The samples in this work were analysed using energy dispersive spectroscopy (EDS) with the aim of identifying the presence of ASR gels in the cracks. However, as illustrated in the work, the analyses were inconclusive as the concentration of elements analysed varied seemingly randomly over the points where the readings were taken. It is therefore recommended that an elemental mapping is performed on future samples as this would

enable to see where each element analysed is more concentrated when overlain on the respective electron micrograph.

6. Current structures

   It is recommended to undertake field studies on structures built, over recent years, with concrete containing the reactive greywacke fine and coarse aggregates.

# 6 References

Addis, B. & Goodman, J., 2009. Concrete mix design. In *Fulton's Concrete Technology*. Midrand: Cement and concrete institute, pp. 219–228.

Afrisam, 2015. Aggregate. In *Afrisam technical Guide*. pp. 32–49. Available at: http://www.afrisam.co.za/media/76323/Aggregrate___Technical_Reference_Guide.pdf.

Alexander, M. & Mindess, S., 2005. *Aggregates in Concrete*, New York: Taylor and Francis.

ASTM international. (2016). ASTM C33/C33M-16 Standard specification for concrete aggregates 1. http://doi.org/10.1520/C0033

ASTM international. (2010). ASTM C227-10 Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations ( Mortar-Bar Method ) 1, *i*. http://doi.org/10.1520/C0227-10.2.

ASTM international. (2007). ASTM C289-07 StandardTest Method for Potential Alkali-Silica Reactivity of Aggregates ( Chemical. http://doi.org/10.1520/C0289-07.2

ASTM international. (2011). ASTM C441/C441M-11 Standard Test Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the, *i*, 1–3. http://doi.org/10.1520/C0441

ASTM international. (2013). ASTM C511-13 Standard Specification for Mixing Rooms , Moist Cabinets , Moist Rooms , and Water, 5–7. http://doi.org/10.1520/C0511-13.2

ASTM international. (2012). ASTM C1073-12 Standard Test Method for Hydraulic Activity of Slag Cement by Reaction with Alkali 1, (Note 2), 4–6. http://doi.org/10.1520/C1073-12.2

ASTM international. (2014). ASTM C1260-14 Standard Test Method for Potential Alkali Reactivity of Aggregates ( Mortar-Bar, 1–5. http://doi.org/10.1520/C1260-14.2

ASTM international. (2015). ASTM C1293-08b Standard Test Method for Determination of Length Change of Concrete Due to Alkali-, (Reapproved), 1–7. http://doi.org/10.1520/C1293-08BR15.2

ASTM international. (2013). ASTM C1567-13 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate ( Accelerated Mortar-Bar Method ) 1, *2013*, 1–6. http://doi.org/10.1520/C1567-13.2

ASTM international. (2016). ASTM C1778-16 Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction. http://doi.org/10.1520/C1778-16.2

Binal, A., 2015. The pessimum ratio and aggregate size effects on alkali silica reaction. *Procedia Earth and Planetary Science*, 15, pp.725–731.

Blight, G. & Alexander, M., 2011. *Alkali-Aggregate Reaction and Structural Damage to Concrete*, London: CRC Press.

British, S. (2002). BS EN 196-1:1995 Methods of testing cement — Part 1 : Determination of strength.

Chen, C., & Yang, W. (n.d.). Mitigation of Alkali-Silica Reaction in Mortar with Limestone Addition and Carbonation, *1*.

Gao, X.X. et al., 2013. Cement and Concrete Research Alkali – silica reaction ( ASR ) expansion : Pessimum effect versus scale effect. *Cement and Concrete Research*, 44, pp.25–33. Available at: http://dx.doi.org/10.1016/j.cemconres.2012.10.015.

Gautam, B.P. et al., 2017. Effect of coarse aggregate grading on the ASR expansion and damage of concrete. *Cement and Concrete Research*, 95, pp.75–83. Available at: http://dx.doi.org/10.1016/j.cemconres.2017.02.022.

Gholizadeh, A., Robert, J. & Rajabipour, F., 2016. Cement and Concrete Research An extended chemical index model to predict the fl y ash dosage necessary for mitigating alkali – silica reaction in concrete. *Cement and Concrete Research*, 82, pp.1–10. Available at: http://dx.doi.org/10.1016/j.cemconres.2015.12.014.

Giaccio, G. et al., 2008. Mechanical behavior of concretes damaged by alkali-silica reaction. , 38, pp.993–1004.

Grieve, G., 2009. Cementitious materials. In *Fulton's Concrete Technology*. Midrand: Cement and concrete institute, pp. 1–16.

Grieve, G., 2009. Aggregates for concrete. In *Fulton's Concrete Technology*. Midrand: Cement and concrete institute, pp. 25–61.

Guthrie, G.D. & Carey, J.W., 1997. A simple environmentally friendly and chemically specific method for the identification and evaluation of the alkali-silica reaction. *Cement and Concrete Research*, 27, pp.1407–1417.

Ichikawa, T., 2009. Alkali – silica reaction , pessimum effects and pozzolanic effect. *Cement and Concrete Research*, 39(8), pp.716–726. Available at: http://dx.doi.org/10.1016/j.cemconres.2009.06.004.

Ichikawa, T. & Miura, M., 2007. Modified model of alkali-silica reaction. , 37, pp.1291–1297.

Islam, M.S. & Ghafoori, N., 2015. Relation of ASR-induced expansion and compressive strength of concrete. *Materials and Structures*, pp.4055–4066. Available at: http://dx.doi.org/10.1617/s11527-014-0465-6.

Lindgård, J., Andiç-çak, Ö., Fernandes, I., Rønning, T. F., & Thomas, M. D. A. (2012). Cement and Concrete Research Alkali – silica reactions ( ASR ): Literature review on parameters influencing laboratory performance testing, *42*, 223–243. http://doi.org/10.1016/j.cemconres.2011.10.004

Lindgård, J. et al., 2010. The EU "PARTNER" Project - European standard tests to prevent alkali reactions in aggregates: Final results and recommendations. *Cement and Concrete Research*, 40(4), pp.611–635. Available at: http://dx.doi.org/10.1016/j.cemconres.2009.09.004.

McDonald, M., 2009. Control of concrete quality. In *Fulton's Concrete Technology*. Midrand: Cement and concrete institute, pp. 287–295.

Multon, S. et al., 2010. Effects of aggregate size and alkali content on ASR expansion. *Cement and Concrete Research*, 40(4), pp.508–516. Available at: http://dx.doi.org/10.1016/j.cemconres.2009.08.002.

Nixon, P. J. (2000). RILEM Recommended Test Method : AAR-4 . 1 — Detection of Potential Alkali-Reactivity — 60 ° C Test Method for Aggregate Combinations Using Concrete Prisms. http://doi.org/10.1007/978-94-017-7252-5

Nixon, P. J. (2000). RILEM Recommended Test Method : AAR-3 — Detection of Potential Alkali-Reactivity — 38 ° C Test Method for Aggregate Combinations Using Concrete Prisms. http://doi.org/10.1007/978-94-017-7252-5

Nixon, P. J. (n.d.). RILEM Recommended Test Method : AAR-2 — Detection of Potential Alkali-Reactivity — Accelerated Mortar-Bar Test Method for Aggregates. http://doi.org/10.1007/978-94-017-7252-5

Oberholster, B., 2009. Alkali-silica reaction. In *Fulton's Concrete Technology*. Midrand: Cement and concrete institute, pp. 189–218.

Owsiak, Z., 2016. The role of lithium compounds in mitigating alkali-gravel aggregate reaction. , 115, pp.299–303.

Perrie, B., 2009. Strength of hardened concrete. In *Fulton's Concrete Technology*. Midrand: Cement and concrete institute, pp. 97–110.

Poyet, S. et al., 2016. Influence of Water on Alkali-Silica Reaction : Experimental Study and Numerical Simulations.

Rajabipour, F. et al., 2015. Cement and Concrete Research Alkali – silica reaction : Current understanding of the reaction mechanisms and the knowledge gaps. *Cement and Concrete Research*, 76, pp.130–146. Available at: http://dx.doi.org/10.1016/j.cemconres.2015.05.024.

Ramezianianpour, A. & Hooton, R.D., 2014. Cement & Concrete Composites A study on hydration , compressive strength , and porosity of Portland- limestone cement mixes containing SCMs. *CEMENT AND CONCRETE COMPOSITES*, 51, pp.1–13. Available at: http://dx.doi.org/10.1016/j.cemconcomp.2014.03.006.

Ramyar, K. & Topal, A., 2005. Effects of aggregate size and angularity on alkali – silica reaction. , 35, pp.2165–2169.

RILEM, 2016. *RILEM Recommendations for the Prevention of Damage by Alkali- Aggregate Reactions in New Concrete Structures* P. J. Nixon & I. Sims, eds., Springer.

SABS Standards Division. (2006). SANS 5863:2006 SOUTH AFRICAN NATIONAL STANDARD Concrete tests — Compressive strength of hardened concrete.

SABS Standards Division. (2006). SANS 6155:2006 SOUTH AFRICAN NATIONAL STANDARD Effect of extenders, used with cement, on the reduction of expansion caused by alkali-silica reaction (accelerated mortar prism method).

SABS Standards Division. (2006). SANS 6245:2006 SOUTH AFRICAN NATIONAL STANDARD Potential reactivity of aggregates with alkalis (accelerated mortar prism method).

Saha, A. K., & Sarker, P. K. (2016). Expansion due to alkali-silica reaction of ferronickel slag fine aggregate in OPC and blended cement mortars. *Construction and Building Materials*, *123*, 135–142. http://doi.org/10.1016/j.conbuildmat.2016.06.144

Shafaatian, S.M.H. et al., 2013. How does fly ash mitigate alkali – silica reaction ( ASR ) in accelerated mortar bar test. *Cement and Concrete Composites*, 37, pp.143–153. Available at: http://dx.doi.org/10.1016/j.cemconcomp.2012.11.004.

Shehata, M.H. & Thomas, M.D.A., 2000. The effect of fly ash composition on the expansion of concrete due to alkali ± silica reaction. , 30.

Thomas, M., 2011. The effect of supplementary cementing materials on alkali-silica reaction : A review. *Cement and Concrete Research*, 41(12), pp.1224–1231. Available at: http://dx.doi.org/10.1016/j.cemconres.2010.11.003.

Thomas, M. et al., 2006. Test methods for evaluating preventive measures for controlling expansion due to alkali-silica reaction in concrete. *Cement and Concrete Research*, 36(10), pp.1842–1856.

Trtik, P. et al., 2013. Density mapping of hardened cement paste using ptychographic X-ray computed tomography. *Cement and Concrete Composites*, 36, pp.71–77. Available at: http://dx.doi.org/10.1016/j.cemconcomp.2012.06.001.

Vollpracht, A., Soutsos, M. & Kanavaris, F., 2018. Strength development of GGBS and fly ash concretes and applicability of fib model code ’ s maturity function – A critical review. *Construction and Building Materials*, 162, pp.830–846. Available at: https://doi.org/10.1016/j.conbuildmat.2017.12.054.

Yurtdas, I. et al., 2013. Influence of alkali silica reaction ( ASR ) on mechanical properties of mortar. , 47, pp.165–174.

Wang, S. (2015). Cofired biomass fly ashes in mortar: Reduction of Alkali Silica Reaction (ASR) expansion, pore solution chemistry and the effects on compressive strength. *Construction and Building Materials*, *82*, 123–132. http://doi.org/10.1016/j.conbuildmat.2015.02.021

# Appendices

# Appendix A: ethics form

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

## APPLICATION FORM

**Please Note:**
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook**(available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/usr/ebe/research/ethics.pdf

| | | |
|---|---|---|
| **APPLICANT'S DETAILS** | | |
| Name of principal researcher, student or external applicant | | Zubair M. LALL MAHOMED |
| Department | | Civil Engineering |
| Preferred email address of applicant: | | llmuh002@myuct.ac.za |
| If a Student | Your Degree: e.g., MSc, PhD, etc., | MSc Civil Structural Engineering |
| | Name of Supervisor (if supervised): | Prof Mark ALEXANDER |
| If this is a researchcontract, indicate the source of funding/sponsorship | | CoMSIRU |
| Project Title | | Alkali Aggregate Reaction in Western Cape Concrete Mixes |

**I hereby undertake to carry out my research in such a way that:**

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

| **SIGNED BY** | Full name | Signature | Date |
|---|---|---|---|
| **Principal Researcher/ Student/External applicant** | Muhammad Zubair LALLMAHOMED | | **12 Oct 2016** |

| **APPLICATION APPROVED BY** | Full name | Signature | Date |
|---|---|---|---|
| **Supervisor** (where applicable) | **Mark Alexander** | | **12 Oct 2016** |
| **HOD (or delegated nominee)**<br>Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (Including Honours). | M Vandarschun<br>~~Click here to enter text.~~ | | 31/10/16<br>Click here to enter a date. |
| **Chair : Faculty EIR Committee**<br>For applicants other than undergraduate students who have answered YES to any of the above questions. | Click here to enter text. | | Click here to enter a date. |

# Appendix B: material data

Relevant information regarding the materials used in this research are provided in the following paragraphs

## B1: cement, CEM II A/L 52.5N (from PPC Ltd)

- Relative density of 3.14
- Blaine of 400 $m^2$/kg
- Sodium oxide equivalent of 0.71%
- Potassium oxide content of 0.72%
- Sodium oxide content of 0.24%

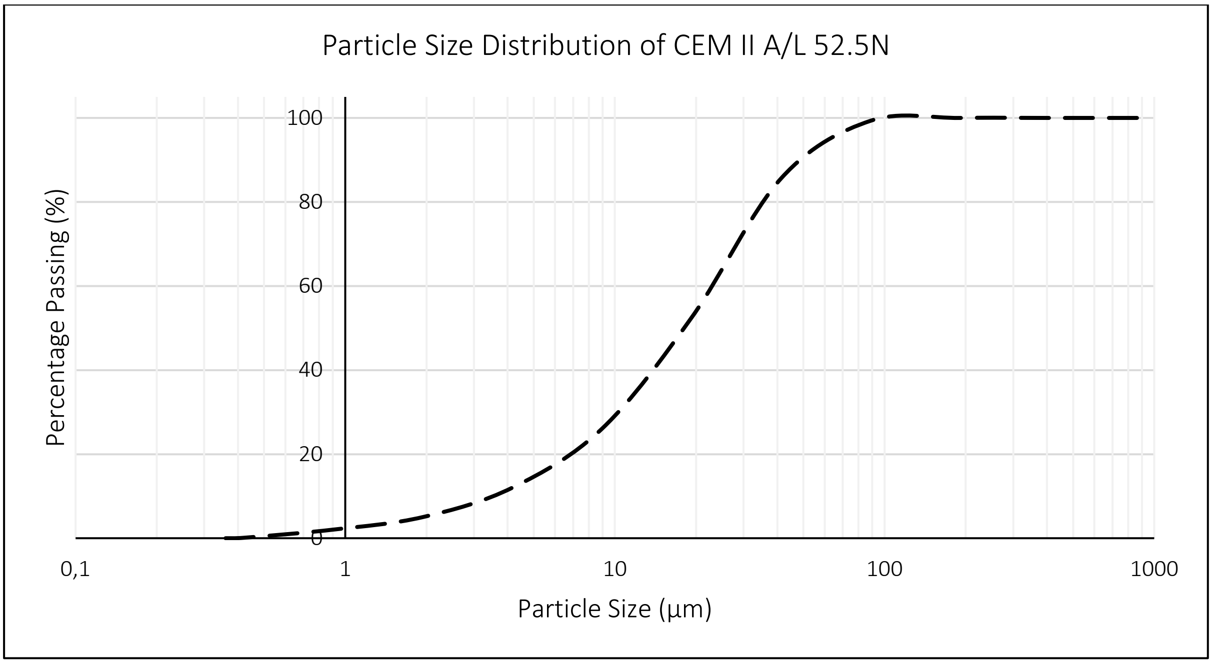

*Figure B1: Particle size distribution of CEM II A/L 52.5N*

## B2: fly ash, Durapozz (from Ash Resources)

- Relative density of 2.2
- Sodium oxide content of 0.2-0.8%
- Potassium oxide content of 0.5-1.0%
- Sodium equivalent of about 1.0%
- Releasable alkali content of 0.2-0.5%

## B3: ground granulated corex slag (from PPC Ltd)

- Relative density of 2.9
- Sodium equivalent of 0.4%
- Blaine 4000 $cm^2$/g

## B4: limestone filler, Kulubrite 10 (from Idwala Industrial holdings)

- Relative density of 2.7
- Calcium carbonate content of 95.0%

- Magnesium carbonate content of 4.0%
- Mean particle size 10μm

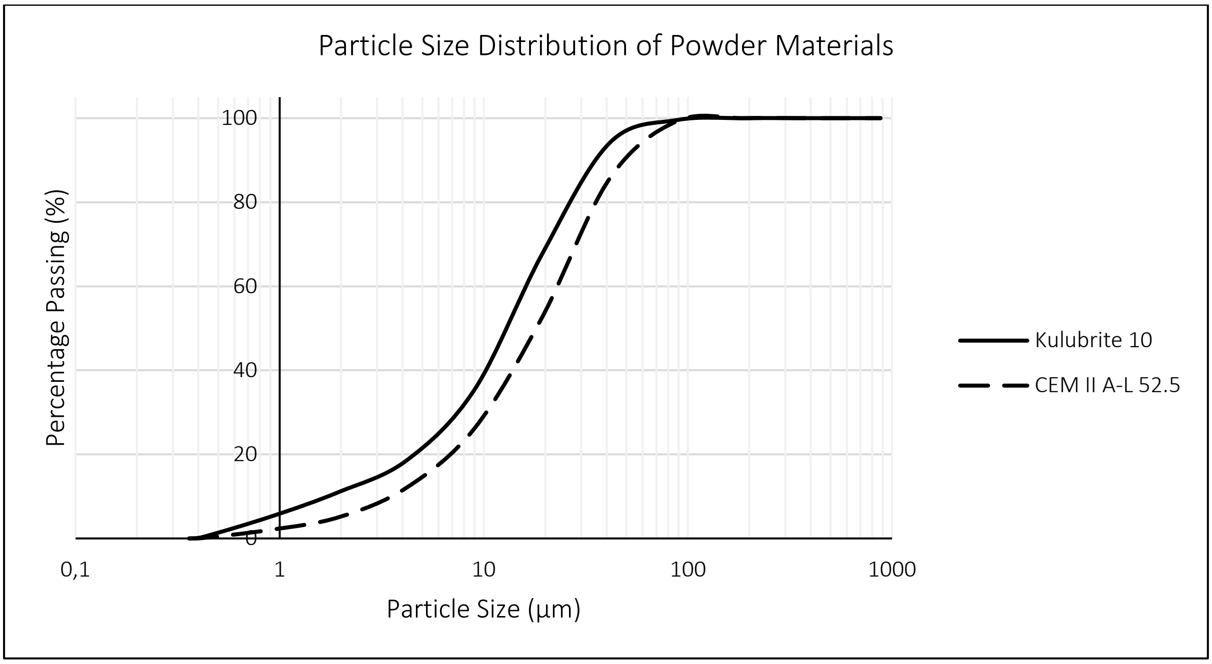

*Figure B2: Particle size distribution of Kulubrite 10*

### B5: non-reactive aggregate, Philippi dune sand

- Relative density of 2.64
- Fineness modulus of 2.05

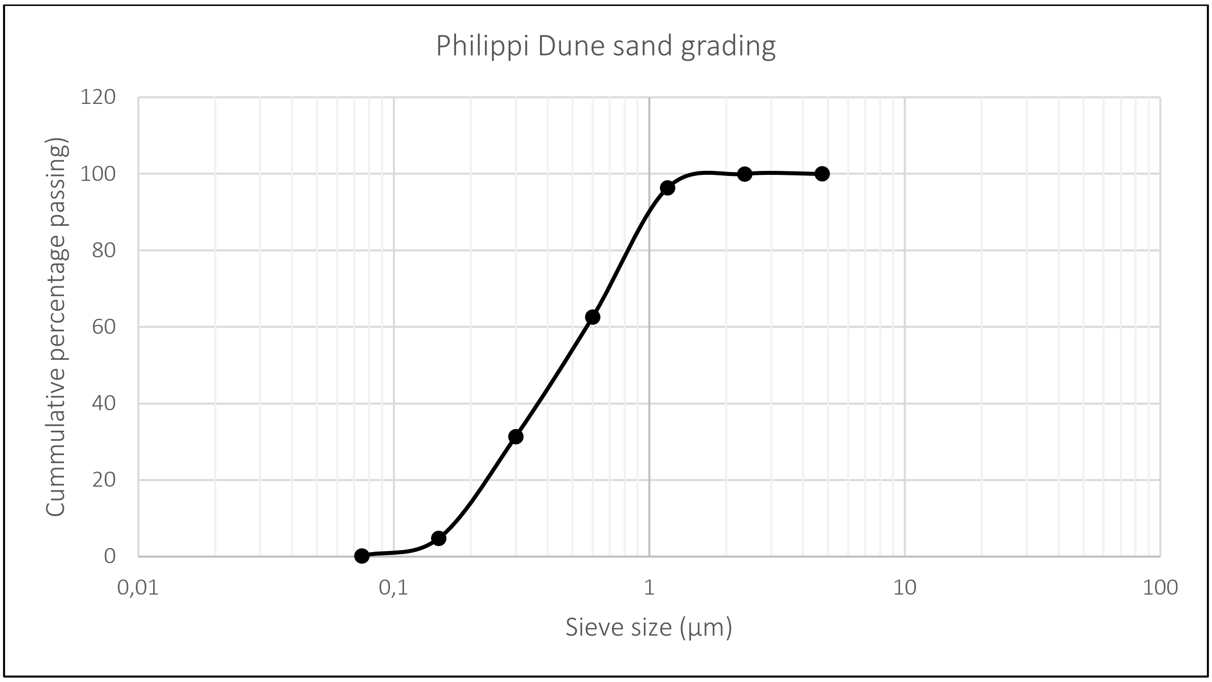

*Figure B3: Particle size distribution of Philippi dune sand*

### B6: greywacke aggregate

- Relative density of 2.72

- Fineness modulus of 3.12

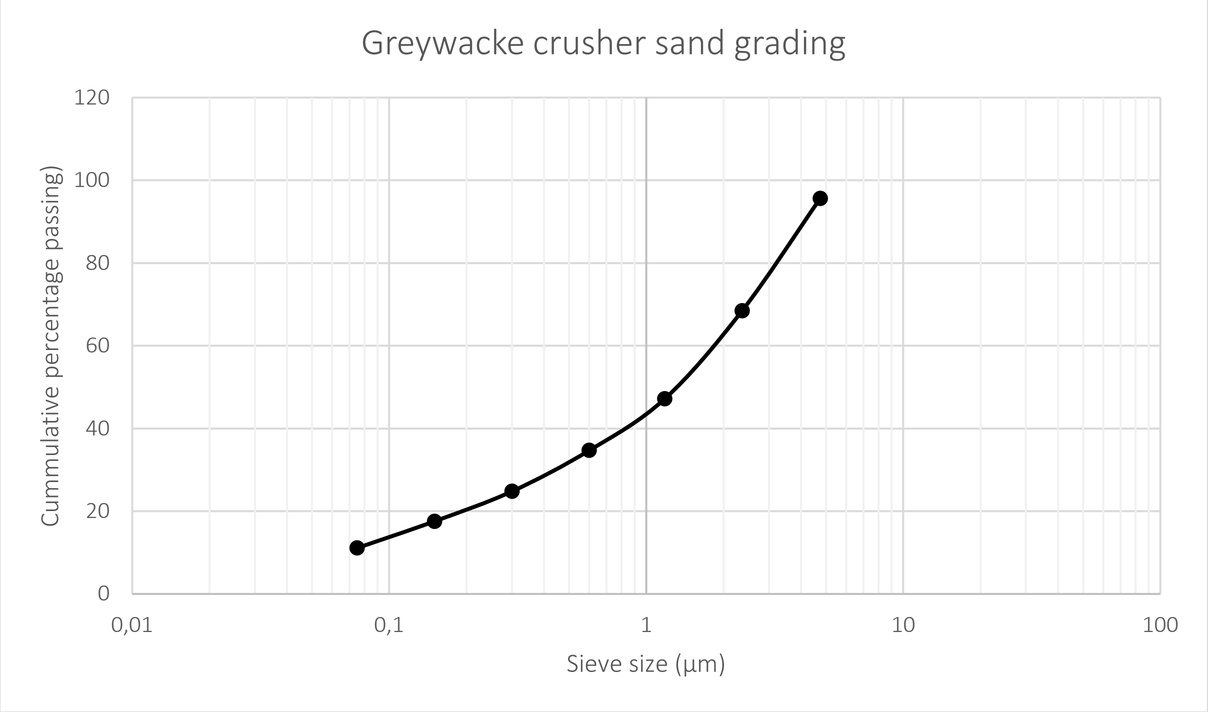

*Figure B4: Particle size distribution of greywacke crusher sand*

### B7: superplasticiser, Chryso Premia 310 (from Chryso SAF (Pty) Ltd)

- Relative density of 1.05
- Sodium equivalent of 1.0%

# Appendix C: modified AMBT mix design

The detailed mix design of the preliminary mixes in Stage 1 – Phase A are provided in Table C1. Table C2 and C3 following provide the mix design of mixes in Phase B and C respectively.

*Table C1: Detailed mix proportions of mixes in Stage 1 - Phase A*

| Constituent | Mix A0 | | Mix A1 | | Mix A2 | | Mix A3 | |
|---|---|---|---|---|---|---|---|---|
| | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres |
| CEM II A-L 52.5N | 618,9 | 197,1 | 618,9 | 197,1 | 618,2 | 196,9 | 617,4 | 196,6 |
| Water | 290,9 | 290,9 | 290,9 | 290,9 | 290,5 | 290,5 | 290,2 | 290,2 |
| 9.5mm greywacke | - | - | 835,6 | 307,2 | 834,5 | 306,8 | 833,5 | 306,4 |
| Greywacke crusher sand | 1392,6 | 512,0 | 557,0 | 204,8 | 445,1 | 163,6 | 333,4 | 122,6 |
| Philippi dune sand | - | - | 0,0 | - | 111,3 | 42,1 | 222,3 | 84,2 |
| DuraPozz | - | - | - | - | - | - | - | 0,0 |
| PPC GGCS | - | - | - | - | - | - | - | 0,0 |
| Inert filler | - | - | - | - | - | - | - | 0,0 |
| Chryso Premia 310 | 1,1 | 1,0 | - | - | - | - | - | 0,0 |
| Total | 2303,5 | 1001,0 | 2302,4 | 1000,0 | 2299,6 | 1000,0 | 2296,7 | 1000,0 |
| Cement alkali | 4,3 | - | 4,3 | - | 4,3 | - | 4,3 | - |
| Alkali from SP | 0,0 | - | - | - | - | - | - | - |
| Water content of SP | - | 0,8 | - | - | - | - | - | - |
| Specified amount | 6,2 | - | 6,2 | - | 6,2 | - | 6,2 | - |
| Extra alkali | 1,8 | - | 1,9 | - | 1,9 | | 1,9 | - |
| Extra NaOH | 2,4 | | 2,4 | | 2,4 | | 2,4 | |

*Table C1 continued*

| Constituent | Mix A4 | | Mix A5 | | Mix A6 | |
|---|---|---|---|---|---|---|
| | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres |
| CEM II A-L 52.5N | 617,2 | 196,6 | 617,0 | 196,5 | 616,8 | 196,4 |
| Water | 290,1 | 290,1 | 290,0 | 290,0 | 289,9 | 289,9 |
| 9.5mm greywacke | 833,2 | 306,3 | 833,0 | 306,2 | 832,7 | 306,1 |
| Greywacke crusher sand | 305,5 | 112,3 | 277,7 | 102,1 | 249,8 | 91,8 |
| Philippi dune sand | 250,0 | 94,7 | 277,7 | 105,2 | 305,3 | 115,7 |
| DuraPozz | - | - | - | - | - | - |
| PPC GGCS | - | - | - | - | - | - |
| Inert filler | - | - | - | - | - | - |
| Chryso Premia 310 | - | - | - | - | - | - |
| Total | 2296,0 | 1000,0 | 2295,3 | 1000,0 | 2294,6 | 1000,0 |
| Cement alkali | 4,3 | - | 4,3 | - | 4,3 | - |
| Alkali from SP | - | - | - | - | - | - |
| Water content of SP | - | - | - | - | - | - |
| Specified amount | 6,2 | - | 6,2 | - | 6,2 | - |
| Extra alkali | 1,9 | - | 1,9 | - | 1,9 | - |
| Extra NaOH | 2,4 | | 2,4 | | 2,4 | |

*Table C1 continued*

| Constituent | Mix A7 | | Mix A8 | | Mix A9 | |
|---|---|---|---|---|---|---|
| | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres |
| CEM II A-L 52.5N | 616,6 | 196,4 | 615,9 | 196,1 | 615,1 | 195,9 |
| Water | 289,8 | 289,8 | 289,5 | 289,5 | 289,1 | 289,1 |
| 9.5mm greywacke | 832,5 | 306,1 | 831,4 | 305,7 | 830,4 | 305,3 |
| Greywacke crusher sand | 222,0 | 81,6 | 110,9 | 40,8 | 0,0 | 0,0 |
| Philippi dune sand | 333,0 | 126,1 | 443,4 | 168,0 | 553,6 | 209,7 |
| DuraPozz | - | - | - | - | - | - |
| PPC GGCS | - | - | - | - | - | - |
| Inert filler | - | - | - | - | - | - |
| Chryso Premia 310 | - | - | - | - | - | - |
| Total | 2293,9 | 1000,0 | 2291,1 | 1000,0 | 2288,2 | 1000,0 |
| Cement alkali | 4,3 | - | 4,3 | - | 4,3 | - |
| Alkali from SP | - | - | - | - | - | - |
| Water content of SP | - | - | - | - | - | - |
| Specified amount | 6,2 | - | 6,2 | - | 6,2 | - |
| Extra alkali | 1,8 | - | 1,8 | - | 1,8 | - |
| Extra NaOH | 2,4 | | 2,4 | | 2,4 | |

*Table C2: Detailed mix proportions of mixes in Stage1 - Phase B*

| Constituent | Mix B1 (40 CS) | | Mix B2 (50 CS) | | Mix B3 (60 CS) | |
|---|---|---|---|---|---|---|
| | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres |
| CEM II A-L 52.5N | 367,8 | 117,1 | 306,0 | 97,5 | 244,4 | 77,8 |
| Water | 288,1 | 288,1 | 287,7 | 287,7 | 287,2 | 287,2 |
| 9.5mm greywacke | 827,6 | 304,3 | 826,3 | 303,8 | 824,9 | 303,3 |
| Greywacke crusher sand | 275,9 | 101,4 | 275,4 | 101,3 | 275,0 | 101,1 |
| Philippi dune sand | 275,9 | 104,5 | 275,4 | 104,3 | 275,0 | 104,2 |
| DuraPozz | - | 0,0 | | 0,0 | | 0,0 |
| PPC GGCS | 245,2 | 84,6 | 306,0 | 105,5 | 366,6 | 126,4 |
| Inert filler | - | 0,0 | | 0,0 | | 0,0 |
| Chryso Premia 310 | - | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| Total | 2280,5 | 1000,0 | 2276,8 | 1000,0 | 2273,1 | 1000,0 |
| Cement alkali | 2,6 | - | 2,1 | - | 1,7 | - |
| SCMs alkali | 1,0 | - | 1,2 | - | 1,5 | - |
| Alkali from SP | - | - | - | - | 0,0 | - |
| Water content of SP | - | - | - | - | | - |
| Specified amount | 3,7 | - | 3,1 | - | 2,4 | - |
| Extra alkali | 1,1 | - | 0,9 | - | 0,7 | - |
| Extra NaOH | 1,4 | | 1,2 | | 0,9 | |

*Table C2 continued*

| Constituent | Mix B4 (20 FA) | | Mix B5 (30 FA) | | Mix B6 (40 FA) | |
|---|---|---|---|---|---|---|
| | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres |
| CEM II A-L 52.5N | 485,5 | 154,6 | 421,3 | 134,2 | 358,2 | 114,1 |
| Water | 285,2 | 285,2 | 282,9 | 282,9 | 280,6 | 280,6 |
| 9.5mm greywacke | 819,2 | 301,2 | 812,5 | 298,7 | 805,9 | 296,3 |
| Greywacke crusher sand | 273,1 | 100,4 | 270,8 | 99,6 | 268,6 | 98,8 |
| Philippi dune sand | 273,1 | 103,4 | 270,8 | 102,6 | 268,6 | 101,8 |
| DuraPozz | 121,4 | 55,2 | 180,6 | 82,1 | 238,8 | 108,5 |
| PPC GGCS | - | - | - | - | - | - |
| Inert filler | - | - | - | - | - | - |
| Chryso Premia 310 | - | - | - | - | - | - |
| Total | 2257,4 | 1000,0 | 2238,9 | 1000,0 | 2220,7 | 1000,0 |
| Cement alkali | 3,4 | - | 2,9 | - | 2,5 | - |
| SCMs alkali | 1,2 | - | 1,8 | - | 2,4 | - |
| Alkali from SP | - | - | - | - | - | - |
| Water content of SP | - | - | - | - | - | - |
| Specified amount | 4,9 | - | 4,2 | - | 3,6 | - |
| Extra alkali | 1,5 | - | 1,3 | - | 1,1 | - |
| Extra NaOH | 1,9 | | 1,6 | | 1,4 | |

*Table C3: Final mix proportions of mixes in Stage 1 - Phase C*

| Constituent | Mix C1 (lime 20) | | Mix C2 (lime 30) | | Mix C3 (lime 40) | | Mix C4 (lime 50) | | Mix C5 (lime 60) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres |
| CEM II A-L 52.5N | 490,5 | 156,2 | 427,8 | 136,2 | 365,5 | 116,4 | 303,6 | 96,7 | 242,2 | 77,1 |
| Water | 288,2 | 288,2 | 287,2 | 287,2 | 286,3 | 286,3 | 285,4 | 285,4 | 284,5 | 284,5 |
| 9.5mm greywacke | 827,7 | 304,3 | 825,1 | 303,3 | 822,4 | 302,4 | 819,9 | 301,4 | 817,3 | 300,5 |
| Greywacke crusher sand | 275,9 | 101,4 | 275,0 | 101,1 | 274,1 | 100,8 | 273,3 | 100,5 | 272,4 | 100,2 |
| Philippi dune sand | 275,9 | 104,5 | 275,0 | 104,2 | 274,1 | 103,8 | 273,3 | 103,5 | 272,4 | 103,2 |
| DuraPozz | - | - | - | - | - | - | - | - | - | - |
| PPC GGCS | - | - | - | - | - | - | - | - | - | - |
| Inert filler | 122,6 | 45,4 | 183,3 | 67,9 | 243,7 | 90,3 | 303,6 | 112,5 | 363,2 | 134,5 |
| Chryso Premia 310 | - | - | - | - | - | - | - | - | - | - |
| Total | 2280 | 1000 | 2273 | 1000 | 2266 | 1000 | 2259 | 1000 | 2252 | 1000 |
| Cement alkali | 3,4 | - | 3,0 | - | 2,6 | - | 2,1 | - | 1,7 | - |
| SCMs alkali | - | - | - | - | - | - | - | - | - | - |
| Alkali from SP | - | - | - | - | - | - | - | - | - | - |
| Water content of SP | - | - | - | - | - | - | - | - | - | - |
| Specified amount | 4,9 | - | 4,3 | - | 3,7 | - | 3,0 | - | 2,4 | - |
| Extra alkali | 1,5 | - | 1,3 | - | 1,1 | - | 0,9 | - | 0,7 | - |
| Extra NaOH | 1,9 | | 1,7 | | 1,4 | | 1,2 | | 0,9 | |

# Appendix D: long-term performance test mix design

The C&CI method was followed to determine the mix design for the long-term testing specimens. Table D1 below details the variables of the long-term specimens.

*Table D1: Test variables of long-term specimens*

| Mix no | Cement type | Fine Aggregate blend |
|---|---|---|
| D0 | 100% CEM II A/L 52.5N | Only dune sand |
| D1 | 100% CEM II A/L 52.5N | 50/50 Dune sand/Crusher sand |
| D2 | 100% CEM II A/L 52.5N boosted alkali content | 50/50 Dune sand/Crusher sand |
| D3 | 80% CEM II A/L 52.5N & 20% fly ash | 50/50 Dune sand/Crusher sand |
| D4 | 50% CEM II A/L 52.5N & 50% GGCS | 50/50 Dune sand/Crusher sand |

## D1: target strength

The first step of the mix design is to choose the strength of the concrete mix. In this research, a characteristic strength of 30MPa was chosen as it depicts common reinforced concrete strength requirements.

However, the target strength of the concrete should be slightly increased to allow for a margin of error in the strength. This is described as the target strength and was calculated based on McDonald (2009). Under the assumption of a ‘good’ site control, a standard deviation of 5MPa was suggested from Table 16:1, McDonald (2009). The target strength which need to be achieved was therefore calculated as follows:

$$f_{cu} = f_{cu,charac} + 1.64 \times SD$$
$$f_{cu} = 30 + 1.64 \times 5$$
$$f_{cu} \approx 40\ MPa$$

## D2: material proportioning

*Water content*

As explained in Section 3.2.2, the water content was chosen based on the type of sand used, coarse aggregate size (19 mm) and slump (75 mm). The use of a blend of crusher sand and Philippi dune sand, made for a sand of excellent quality, with a fineness modulus of 2.59 which offered a wide particle distribution as well as a good workability. The water content as suggested by Table 11.2: Addis & Goodman (2009) was 185 l/m$^3$. However, for the control mix, the sand quality would be deemed of a lower quality as only dune sand is used. Nevertheless, it was decided to keep the water content constant and adjust the slump later on through the use of superplasticiser.

*Binder content*

Based on the strength required and the strength development curve provided by the cement manufacturer, it was found that for mix D0 to D2 a w/b ratio of 0.62 would be satisfactory while for mix D3 and D4 a w/b ratio of 0.56 was chosen to accommodate for the addition of fly ash and GGCS in those mixes respectively. Using the chosen water to binder ratio and water content of the mixes, the total mass of binder was calculated as follows.

$$M_b = \frac{water\ content}{\frac{water}{binder} ratio}$$

*Coarse aggregate content*

As previously stated, a CBD of 1450 kg/m$^3$ was used for the coarse aggregate. Based on the desired slump (70-100mm), placing requirement (moderate vibration) and maximum size of stone (19mm crushed greywacke), a 'K' value of 1.00 was recommended (Table 11.4; Addis & Goodman, 2009). The effective fineness modulus of the sand blend was determined to be 2.59 while the fineness modulus of dune sand was 2.05. Consequently, a mass of stone per cubic metre of was calculated as follows.

$$M_{ca} = CBD \times (K - 0.1FM)$$

Moreover, it was suggested that the mass of stone should be increased by a further 4% due to the inclusion of 20% fly ash in the mix D3.

*Fine aggregate content*

The fine aggregate was then calculated based on the remaining volume required to achieve a mix volume of 1 cubic metre.

$$M_{fa} = RD_{fa} \times 1000 \times \left(1 - \frac{M_c}{RD_c \times 1000} - \frac{M_{cement\ extender}}{RD_{cement\ extender} \times 100} - \frac{M_{ca}}{RD_{ca} \times 1000} - \frac{M_w}{1 \times 1000}\right)$$

## D3: final mix proportions

The final mix proportion from the C&CI method are as follows are as detailed in the table below.

*Table D2 Mix proportion of long term specimens*

| Constituent | Mix D0 | | Mix D1 | | Mix D2 | | Mix D3 | | Mix D4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres |
| CEM II A-L 52.5N | 298,4 | 95,0 | 298,4 | 95,0 | 298,4 | 95,0 | 264,3 | 84,2 | 165,2 | 52,6 |
| Water | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 |
| 19mm greywacke | 1152,8 | 423,8 | 1074,5 | 395,0 | 1074,5 | 395,0 | 1117,4 | 410,8 | 1074,5 | 395,0 |
| Greywacke crusher sand | - | - | 435,4 | 160,1 | 435,4 | 160,1 | 388,6 | 142,9 | 416,0 | 152,9 |
| Philippi dune sand | 781,9 | 296,2 | 435,4 | 164,9 | 435,4 | 164,9 | 388,6 | 147,2 | 416,0 | 157,6 |
| DuraPozz FA | - | - | - | - | - | - | 66,1 | 30,0 | - | - |
| PPC GGCS | - | - | - | - | - | - | - | - | 165,2 | 57,0 |
| Inert filler | - | - | - | - | - | - | - | - | - | - |
| Chryso Premia 310 | - | - | - | - | - | - | - | - | - | - |
| Total | 2418 | 1000 | 2429 | 1000 | 2429 | 1000 | 2410 | 1000 | 2422 | 1000 |

However, with the aim of facilitating comparison, one more variable was removed from the mixes and the coarse aggregate content was fixed to 1100 kg/m$^3$. The fine aggregate content was then adjusted accordingly and the final mix proportions are detailed in Table D3.

*Table D3: Final mix proportions of long-term performance test mixes*

| Constituent | Mix D0 | | Mix D1 | | Mix D2 | | Mix D3 | | Mix D4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres | kg/m³ | litres |
| CEM II A-L 52.5N | 298,4 | 95,0 | 298,4 | 95,0 | 298,4 | 95,0 | 264,3 | 84,2 | 165,2 | 52,6 |
| Water | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 | 185,0 |
| 19mm greywacke | 1100,0 | 404,4 | 1100,0 | 404,4 | 1100,0 | 404,4 | 1100,0 | 404,4 | 1100,0 | 404,4 |
| Greywacke crusher sand | - | - | 422,7 | 155,4 | 422,7 | 155,4 | 397,3 | 146,1 | 403,3 | 148,3 |
| Philippi dune sand | 834,7 | 316,2 | 422,7 | 160,1 | 422,7 | 160,1 | 397,3 | 150,5 | 403,3 | 152,8 |
| DuraPozz FA | - | - | - | - | - | - | 66,1 | 30,0 | - | - |
| PPC GGCS | - | - | - | - | - | - | - | - | 165,2 | 57,0 |
| Inert filler | - | - | - | - | - | - | - | - | - | - |
| Chryso Premia 310 | - | - | - | - | - | - | - | - | - | - |
| Total | 2418 | 1001 | 2429 | 1000 | 2429 | 1000 | 2410 | 1000 | 2422 | 1000 |

# Appendix E: detailed AMBT test results

Raw data (for full raw data sheet contact author) and calculated expansion obtained from the modified AMBT tests performed are presented herewith. It is to be noted that target on one side of mix A0 and mix A7 fell during the curing process. The results of this side had to be extrapolated from the preliminary readings taken at earlier ages. With regards to t-test results, please contact author

## E1: detailed modified AMBT test results of Stage 1 – Phase A

*Table E1: modified AMBT test results of mix A0*

| Date | 13 November 2016 | | | 14 November 2016 | | | 28 November 2016 | | | Linear expansion (Ln - $L_1$ )/$L_0$ | 12 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,501 | | | 100,498 | | | 100,499 | | | | 100,498 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,499 | 100,595 | 100,547 | 100,56 | 100,63 | 100,595 | 100,785 | 100,797 | 100,791 | 0,20 | 100,892 | 100,915 | 100,9035 | 0,31 |
| 2 | 100,497 | 100,481 | 100,489 | 100,545 | 100,548 | 100,5465 | 100,763 | 100,754 | 100,7585 | 0,21 | 100,863 | 100,852 | 100,8575 | 0,31 |
| 3 | 100,452 | 100,486 | 100,469 | 100,504 | 100,516 | 100,51 | 100,73 | 100,762 | 100,746 | 0,24 | 100,87 | 100,877 | 100,8735 | 0,36 |
| | | | | | | | Average | | | 0,20 | Average | | | 0,31 |
| | | | | | | | Reactivity | | | Deleteriously reactive | | | | |
| | | | | | | | Standard deviation | | | 0,011 | Standard deviation | | | 0,002 |
| | | | | | | | Std dev/ average (%) | | | 5,573 | Std dev/ average (%) | | | 0,571 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E2: modified AMBT test results of mix A1*

| Date | 17 November 2016 | | | 18 November 2016 | | | 02 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_0$ | 16 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,499 | | | 100,5 | | | 100,498 | | | | 100,498 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,507 | 100,499 | 100,503 | 100,559 | 100,552 | 100,5555 | 100,705 | 100,712 | 100,7085 | 0,16 | 100,75 | 100,844 | 100,797 | 0,24 |
| 2 | 100,496 | 100,492 | 100,494 | 100,556 | 100,552 | 100,554 | 100,669 | 100,688 | 100,6785 | 0,13 | 100,735 | 100,75 | 100,7425 | 0,19 |
| 3 | 100,492 | 100,491 | 100,4915 | 100,548 | 100,566 | 100,557 | 100,688 | 100,751 | 100,7195 | 0,16 | 100,767 | 100,861 | 100,814 | 0,26 |
| | | | | | | | Average | | | 0,15 | Average | | | 0,23 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,020 | Standard deviation | | | 0,036 |
| | | | | | | | Std dev/ average (%) | | | 13,302 | Std dev/ average (%) | | | 15,550 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E3: modified AMBT test of mix A2*

| Date | 17 November 2016 | | | 18 November 2016 | | | 02 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 16 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,495 | | | 100,5 | | | 100,497 | | | | 100,497 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,492 | 100,503 | 100,4975 | 100,555 | 100,564 | 100,5595 | 100,721 | 100,6 | 100,661 | 0,10 | 100,803 | 100,673 | 100,738 | 0,18 |
| 2 | 100,502 | 100,49 | 100,496 | 100,465 | 100,526 | 100,4955 | 100,809 | 100,635 | 100,722 | 0,23 | 100,898 | 100,71 | 100,804 | 0,31 |
| 3 | 100,492 | 100,489 | 100,4905 | 100,549 | 100,542 | 100,5455 | 100,758 | 100,667 | 100,713 | 0,17 | 100,838 | 100,726 | 100,782 | 0,24 |
| | | | | | | | Average | | | 0,17 | Average | | | 0,24 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,063 | Standard deviation | | | 0,065 |
| | | | | | | | Std dev/ average (%) | | | 37,405 | Std dev/ average (%) | | | 26,673 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E4: modified AMBT test results of mix A3 (preliminary)*

| Date | 18 November 2016 | | | 19 November 2016 | | | 03 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_0$ | 17 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,499 | | | 100,499 | | | 100,498 | | | | 100,498 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,505 | 100,496 | 100,5005 | 100,562 | 100,563 | 100,5625 | 100,729 | 100,747 | 100,738 | 0,18 | 100,791 | 100,852 | 100,8215 | 0,26 |
| 2 | 100,497 | 100,495 | 100,496 | 100,55 | 100,574 | 100,562 | 100,681 | 100,757 | 100,719 | 0,16 | 100,773 | 100,878 | 100,8255 | 0,26 |
| 3 | 100,5 | 100,501 | 100,5005 | 100,552 | 100,559 | 100,5555 | 100,677 | 100,848 | 100,7625 | 0,21 | 100,775 | 100,836 | 100,8055 | 0,25 |
| | | | | | | | Average | | | 0,18 | Average | | | 0,26 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,025 | Standard deviation | | | 0,007 |
| | | | | | | | Std dev/ average (%) | | | 13,980 | Std dev/ average (%) | | | 2,659 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | | Check A | | | Okay | | | | |
| | | | | | | SANS 6245 check | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | | Check C | | | Not okay | | | | |
| | | | | | | AAR-2 check | Check D | | | Not okay | | | | |

*Table E5: modified AMBT test results of mix A3 (refined)*

| Date | 28 February 2017 | | | 01 March 2017 | | | 15 March 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 29 March 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,489 | | | 100,496 | | | 100,489 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,488 | 100,472 | 100,48 | 100,557 | 100,546 | 100,5515 | 100,747 | 100,686 | 100,7165 | 0,17 | 100,924 | 100,776 | 100,85 | 0,30 |
| 2 | 100,475 | 100,481 | 100,478 | 100,558 | 100,549 | 100,5535 | 100,745 | 100,702 | 100,7235 | 0,18 | 100,784 | 100,807 | 100,7955 | 0,25 |
| 3 | 100,469 | 100,4845 | 100,4768 | 100,544 | 100,545 | 100,5445 | 100,629 | 100,754 | 100,6915 | 0,15 | 100,669 | 100,865 | 100,767 | 0,23 |
| | | | | | | | Average | | | 0,17 | Average | | | 0,26 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,012 | Standard deviation | | | 0,039 |
| | | | | | | | Std dev/ average (%) | | | 7,215 | Std dev/ average (%) | | | 15,162 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E6: modified AMBT test result of mix A4*

| Date | 28 February 2017 | | | 01 March 2017 | | | 15 March 2017 | | | Linear expansion $(Ln - L_1)/L_o$ | 29 March 2017 | | | Linear expansion $(Ln - L_1)/L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,489 | | | 100,494 | | | 100,49 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,488 | 100,492 | 100,49 | 100,56 | 100,557 | 100,5585 | 100,709 | 100,75 | 100,7295 | 0,17 | 100,759 | 100,812 | 100,7855 | 0,23 |
| 2 | 100,476 | 100,491 | 100,4835 | 100,539 | 100,552 | 100,5455 | 100,688 | 100,681 | 100,6845 | 0,14 | 100,771 | 100,778 | 100,7745 | 0,23 |
| 3 | 100,48 | 100,488 | 100,484 | 100,551 | 100,541 | 100,546 | 100,685 | 100,68 | 100,6825 | 0,14 | 100,669 | 100,865 | 100,767 | 0,22 |
| | | | | | | | Average | | | 0,15 | Average | | | 0,23 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,019 | Standard deviation | | | 0,005 |
| | | | | | | | Std dev/ average (%) | | | 12,587 | Std dev/ average (%) | | | 2,023 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E7: modified AMBT test result of mix A5*

| Date | 02 March 2017 | | | 03 March 2017 | | | 17 March 2017 | | | Linear expansion $(L_n - L_1)/L_o$ | 31 March 2017 | | | Linear expansion $(L_n - L_1)/L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,494 | | | 100,495 | | | 100,492 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,512 | 100,505 | 100,5085 | 100,561 | 100,576 | 100,5685 | 100,605 | 100,817 | 100,711 | 0,15 | 100,753 | 100,919 | 100,836 | 0,27 |
| 2 | 100,488 | 100,499 | 100,4935 | 100,562 | 100,564 | 100,563 | 100,748 | 100,733 | 100,7405 | 0,18 | 100,836 | 100,854 | 100,845 | 0,29 |
| 3 | 100,493 | 100,496 | 100,4945 | 100,553 | 100,564 | 100,5585 | 100,696 | 100,766 | 100,731 | 0,18 | 100,804 | 100,884 | 100,844 | 0,29 |
| | | | | | | | Average | | | 0,17 | Average | | | 0,28 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,019 | Standard deviation | | | 0,010 |
| | | | | | | | Std dev/ average (%) | | | 11,324 | Std dev/ average (%) | | | 3,368 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E8: modified AMBT test results of mix A6*

| Date | 02 March 2017 | | | 03 March 2017 | | | 17 March 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 31 March 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,494 | | | 100,494 | | | 100,492 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,495 | 100,5 | 100,4975 | 100,564 | 100,568 | 100,566 | 100,706 | 100,742 | 100,724 | 0,16 | 100,806 | 100,854 | 100,83 | 0,27 |
| 2 | 100,491 | 100,503 | 100,497 | 100,565 | 100,566 | 100,5655 | 100,738 | 100,702 | 100,72 | 0,16 | 100,834 | 100,801 | 100,8175 | 0,26 |
| 3 | 100,529 | 100,502 | 100,5155 | 100,606 | 100,558 | 100,582 | 100,901 | 100,64 | 100,7705 | 0,19 | 100,912 | 100,724 | 100,818 | 0,24 |
| | | | | | | | Average | | | 0,17 | Average | | | 0,25 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,019 | Standard deviation | | | 0,014 |
| | | | | | | | Std dev/ average (%) | | | 11,066 | Std dev/ average (%) | | | 5,516 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E9: modified AMBT test results of mix A7 (preliminary)*

| Date | 16 November 2016 | | | 17 November 2016 | | | 01 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_0$ | 15 December 2016 | | | Linear expansion (Ln - $L_1$ )/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,502 | | | 100,499 | | | 100,498 | | | | 100,498 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,502 | 100,436 | 100,469 | 100,509 | 100,498 | 100,5035 | 100,862 | 100,648 | 100,755 | 0,25 | 100,898 | 100,78 | 100,839 | 0,34 |
| 2 | 100,503 | 100,568 | 100,5355 | 100,528 | 100,612 | 100,57 | 100,656 | 100,74 | 100,698 | 0,13 | 100,75 | 100,83 | 100,79 | 0,22 |
| 3 | 100,491 | 100,528 | 100,5095 | 100,536 | 100,574 | 100,555 | 100,712 | 100,731 | 100,7215 | 0,17 | 100,822 | 100,825 | 100,8235 | 0,27 |
| | | | | | | | Average | | | 0,21 | Average | | | 0,30 |
| | | | | | | | Reactivity | | | Deleteriously reactive | | | | |
| | | | | | | | Standard deviation | | | 0,060 | Standard deviation | | | 0,047 |
| | | | | | | | Std dev/ average (%) | | | 28,621 | Std dev/ average (%) | | | 15,636 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | | Check A | | | Not okay | | | | |
| | | | | | | SANS 6245 check | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | | Check C | | | Not okay | | | | |
| | | | | | | AAR-2 check | Check D | | | Not okay | | | | |

*Table E10: modified AMBT test results of mix A7 (refined)*

| Date | 04 March 2017 | | | 05 March 2017 | | | 19 March 2017 | | | Linear expansion $(L_n - L_1)/L_o$ | 02 April 2017 | | | Linear expansion $(L_n - L_1)/L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,494 | | | 100,496 | | | 100,497 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,495 | 100,498 | 100,4965 | 100,572 | 100,565 | 100,5685 | 100,762 | 100,71 | 100,736 | 0,17 | 100,771 | 100,852 | 100,8115 | 0,25 |
| 2 | 100,504 | 100,494 | 100,499 | 100,558 | 100,567 | 100,5625 | 100,701 | 100,75 | 100,7255 | 0,16 | 100,797 | 100,856 | 100,8265 | 0,27 |
| 3 | 100,499 | 100,496 | 100,4975 | 100,556 | 100,551 | 100,5535 | 100,672 | 100,657 | 100,6645 | 0,11 | 100,879 | 100,798 | 100,8385 | 0,29 |
| | | | | | | | Average | | | 0,15 | Average | | | 0,27 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,031 | Standard deviation | | | 0,021 |
| | | | | | | | Std dev/ average (%) | | | 21,484 | Std dev/ average (%) | | | 7,778 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E11: modified AMBT test results of mix A8*

| Date | 18 November 2016 | | | 19 November 2016 | | | 03 December 2016 | | | Linear expansion $(L_n - L_1)/L_o$ | 17 December 2016 | | | Linear expansion $(L_n - L_1)/L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,499 | | | 100,499 | | | 100,497 | | | | 100,497 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,499 | 100,504 | 100,5015 | 100,574 | 100,566 | 100,57 | 100,779 | 100,759 | 100,769 | 0,20 | 100,854 | 100,852 | 100,853 | 0,29 |
| 2 | 100,499 | 100,502 | 100,5005 | 100,565 | 100,561 | 100,563 | 100,641 | 100,715 | 100,678 | 0,12 | 100,734 | 100,796 | 100,765 | 0,20 |
| 3 | 100,5 | 100,504 | 100,502 | 100,542 | 100,556 | 100,549 | 100,703 | 100,603 | 100,653 | 0,11 | 100,813 | 100,727 | 100,77 | 0,22 |
| | | | | | | | Average | | | 0,14 | Average | | | 0,24 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,052 | Standard deviation | | | 0,042 |
| | | | | | | | Std dev/ average (%) | | | 36,767 | Std dev/ average (%) | | | 17,848 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E12: modified AMBT test results of mix A9*

| Date | 13 November 2016 | | | 14 November 2016 | | | 28 November 2016 | | | Linear expansion (Ln - $L_1$)/$L_0$ | 12 December 2016 | | | Linear expansion (Ln - $L_1$)/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,501 | | | 100,498 | | | 100,498 | | | | 100,498 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,501 | 100,498 | 100,4995 | 100,55 | 100,552 | 100,551 | 100,676 | 100,681 | 100,6785 | 0,13 | 100,715 | 100,795 | 100,755 | 0,20 |
| 2 | 100,503 | 100,495 | 100,499 | 100,55 | 100,547 | 100,5485 | 100,731 | 100,673 | 100,702 | 0,15 | 100,833 | 100,792 | 100,8125 | 0,26 |
| 3 | 100,493 | 100,507 | 100,5 | 100,546 | 100,57 | 100,558 | 100,671 | 100,738 | 100,7045 | 0,15 | 100,78 | 100,876 | 100,828 | 0,27 |
| | | | | | | | Average | | | 0,14 | Average | | | 0,25 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,013 | Standard deviation | | | 0,036 |
| | | | | | | | Std dev/ average (%) | | | 9,441 | Std dev/ average (%) | | | 14,836 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

T-test comparison, at a confidence level of 95%, between the mixes initial and refined results of mix A3 and mix A7 showed no statistical difference as shown in Table E13.

*Table E13: t-test comparison between initial and refined results of mix A3 and A7*

| mix A3 initial | mix A3 refined | | | mix A7 initial | mix A7 refined | |
|---|---|---|---|---|---|---|
| 0,1765 | 0,172 | | | 0,2525 | 0,1665 | |
| 0,158 | 0,177 | | | 0,129 | 0,162 | |
| 0,208 | 0,154 | | | 0,1675 | 0,11 | |

| t-Test: Two-Sample Assuming Unequal Variances | | | | t-Test: Two-Sample Assuming Unequal Variances | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| | *Variable 1* | *Variable 2* | | | *Variable 1* | *Variable 2* |
| Mean | 0,180833 | 0,167667 | | Mean | 0,183 | 0,146167 |
| Variance | 0,000639 | 0,000146 | | Variance | 0,003993 | 0,000986 |
| Observations | 3 | 3 | | Observations | 3 | 3 |
| Hypothesized Mean Difference | 0 | | | Hypothesized Mean Difference | 0 | |
| df | 3 | | | df | 3 | |
| t Stat | 0,813741 | | | t Stat | 0,904099 | |
| P(T<=t) one-tail | 0,237689 | | | P(T<=t) one-tail | 0,216293 | |
| t Critical one-tail | 2,353363 | | | t Critical one-tail | 2,353363 | |
| P(T<=t) two-tail | 0,475379 | | | P(T<=t) two-tail | 0,432586 | |
| t Critical two-tail | 3,182446 | | | t Critical two-tail | 3,182446 | |
| | | | | | | |
| t<-t crit | - | | | t<-t crit | - | |
| t>t crit | - | | | t>t crit | - | |

## E2: detailed modified AMBT test results of Stage 1 – Phase B

*Table E14: modified AMBT test results of mix B1*

| Date | 04 May 2017 | | | 05 May 2017 | | | 19 May 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 02 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,49 | | | 100,487 | | | 100,492 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,484 | 100,482 | 100,483 | 100,538 | 100,559 | 100,5485 | 100,581 | 100,597 | 100,589 | 0,04 | 100,612 | 100,632 | 100,622 | 0,07 |
| 2 | 100,47 | 100,485 | 100,4775 | 100,544 | 100,554 | 100,549 | 100,615 | 100,605 | 100,61 | 0,06 | 100,605 | 100,611 | 100,608 | 0,06 |
| 3 | 100,489 | 100,488 | 100,4885 | 100,548 | 100,551 | 100,5495 | 100,583 | 100,574 | 100,5785 | 0,02 | 100,557 | 100,613 | 100,585 | 0,03 |
| | | | | | | | Average | | | 0,04 | Average | | | 0,05 |
| | | | | | | | Reactivity | | | Not reactive | | | | |
| | | | | | | | Standard deviation | | | 0,016 | Standard deviation | | | 0,019 |
| | | | | | | | Std dev/ average (%) | | | 42,103 | Std dev/ average (%) | | | 36,183 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check D | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E15: modified AMBT test results of mix B2*

| Date | 04 May 2017 | | | 05 May 2017 | | | 19 May 2017 | | | Linear expansion (Ln - $L_1$ )/$L_0$ | 02 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,49 | | | 100,491 | | | 100,488 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,498 | 100,484 | 100,491 | 100,53 | 100,541 | 100,5355 | 100,556 | 100,564 | 100,56 | 0,03 | 100,564 | 100,561 | 100,5625 | 0,03 |
| 2 | 100,484 | 100,491 | 100,4875 | 100,517 | 100,546 | 100,5315 | 100,548 | 100,542 | 100,545 | 0,02 | 100,551 | 100,562 | 100,5565 | 0,03 |
| 3 | 100,477 | 100,431 | 100,454 | 100,542 | 100,483 | 100,5125 | 100,571 | 100,545 | 100,558 | 0,05 | 100,595 | 100,588 | 100,5915 | 0,08 |
| | | | | | | | Average | | | 0,03 | Average | | | 0,04 |
| | | | | | | | Reactivity | | | Not reactive | | | | |
| | | | | | | | Standard deviation | | | 0,016 | Standard deviation | | | 0,031 |
| | | | | | | | Std dev/ average (%) | | | 52,730 | Std dev/ average (%) | | | 68,543 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check D | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E16: modified AMBT test results of mix B3*

| Date | 06 May 2017 | | | 07 May 2017 | | | 21 May 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 04 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,488 | | | 100,486 | | | 100,491 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,476 | 100,479 | 100,4775 | 100,556 | 100,543 | 100,5495 | 100,562 | 100,556 | 100,559 | 0,00 | 100,568 | 100,566 | 100,567 | 0,01 |
| 2 | 100,472 | 100,462 | 100,467 | 100,534 | 100,53 | 100,532 | 100,556 | 100,529 | 100,5425 | 0,01 | 100,569 | 100,507 | 100,538 | 0,00 |
| 3 | 100,487 | 100,486 | 100,4865 | 100,535 | 100,532 | 100,522 | 100,537 | 100,539 | 100,538 | 0,01 | 100,582 | 100,574 | 100,578 | 0,05 |
| | | | | | | | Average | | | 0,01 | Average | | | 0,02 |
| | | | | | | | Reactivity | | | Not reactive | | | | |
| | | | | | | | Standard deviation | | | 0,004 | Standard deviation | | | 0,026 |
| | | | | | | | Std dev/ average (%) | | | 50,000 | Std dev/ average (%) | | | 116,386 |
| | | | | | | | Check to choose | | | Check B | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check D | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Okay | | | | |

*Table E17: modified AMBT test results of mix B4*

| Date | 06 May 2017 | | | 07 May 2017 | | | 21 May 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 04 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,488 | | | 100,49 | | | 100,489 | | | | 100,489 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,489 | 100,479 | 100,484 | 100,544 | 100,531 | 100,5375 | 100,546 | 100,539 | 100,5425 | 0,01 | 100,565 | 100,548 | 100,5565 | 0,02 |
| 2 | 100,482 | 100,477 | 100,4795 | 100,544 | 100,524 | 100,534 | 100,567 | 100,524 | 100,5455 | 0,01 | 100,572 | 100,554 | 100,563 | 0,03 |
| 3 | 100,465 | 100,479 | 100,472 | 100,519 | 100,537 | 100,528 | 100,531 | 100,566 | 100,5485 | 0,02 | 100,548 | 100,557 | 100,5525 | 0,03 |
| | | | | | | | Average | | | 0,01 | Average | | | 0,03 |
| | | | | | | | Reactivity | | | Not reactive | | | | |
| | | | | | | | Standard deviation | | | 0,008 | Standard deviation | | | 0,005 |
| | | | | | | | Std dev/ average (%) | | | 58,376 | Std dev/ average (%) | | | 19,901 |
| | | | | | | | Check to choose | | | Check B | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check D | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Okay | | | | |

*Table E18: modified AMBT test results of mix B5*

| Date | 09 May 2017 | | | 10 May 2017 | | | 24 May 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 07 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,485 | | | 100,493 | | | 100,489 | | | | 100,491 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,482 | 100,535 | 100,5085 | 100,548 | 100,543 | 100,5455 | 100,556 | 100,559 | 100,5575 | 0,02 | 100,563 | 100,564 | 100,5635 | 0,02 |
| 2 | 100,476 | 100,502 | 100,489 | 100,529 | 100,546 | 100,5375 | 100,537 | 100,532 | 100,5345 | 0,00 | 100,549 | 100,539 | 100,544 | 0,01 |
| 3 | 100,477 | 100,486 | 100,4815 | 100,515 | 100,546 | 100,5305 | 100,527 | 100,543 | 100,535 | 0,01 | 100,535 | 100,546 | 100,5405 | 0,01 |
| | | | | | | | Average | | | 0,01 | Average | | | 0,01 |
| | | | | | | | Reactivity | | | Not reactive | | | | |
| | | | | | | | Standard deviation | | | 0,007 | Standard deviation | | | 0,006 |
| | | | | | | | Std dev/ average (%) | | | 88,235 | Std dev/ average (%) | | | 50,248 |
| | | | | | | | Check to choose | | | Check B | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check D | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Okay | | | | |

*Table E19: modified AMBT test results of mix B6*

| Date | 09 May 2017 | | | 10 May 2017 | | | 24 May 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 07 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,49 | | | 100,489 | | | 100,49 | | | | 100,488 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,483 | 100,486 | 100,4845 | 100,531 | 100,538 | 100,5345 | 100,532 | 100,539 | 100,5355 | 0,00 | 100,535 | 100,546 | 100,5405 | 0,01 |
| 2 | 100,485 | 100,48 | 100,4825 | 100,54 | 100,538 | 100,539 | 100,543 | 100,537 | 100,54 | 0,00 | 100,547 | 100,557 | 100,552 | 0,01 |
| 3 | 100,481 | 100,474 | 100,4775 | 100,537 | 100,535 | 100,536 | 100,529 | 100,552 | 100,5405 | 0,00 | 100,539 | 100,558 | 100,5485 | 0,01 |
| | | | | | | | Average | | | 0,00 | Average | | | 0,01 |
| | | | | | | | Reactivity | | | Not reactive | | | | |
| | | | | | | | Standard deviation | | | 0,002 | Standard deviation | | | 0,004 |
| | | | | | | | Std dev/ average (%) | | | 173,205 | Std dev/ average (%) | | | 33,958 |
| | | | | | | | Check to choose | | | Check B | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Okay | | | | |
| | | | | | | | Check to choose | | | Check D | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Okay | | | | |

## E3: detailed AMBT test results of Stage 1 - Phase C

*Table E20: modified AMBT test results of mix C1*

| Date | 23 May 2017 | | | 24 May 2017 | | | 07 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 21 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,489 | | | 100,488 | | | 100,49 | | | | 100,489 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,485 | 100,474 | 100,4795 | 100,536 | 100,532 | 100,534 | 100,642 | 100,678 | 100,66 | 0,12 | 100,738 | 100,758 | 100,748 | 0,21 |
| 2 | 100,471 | 100,467 | 100,469 | 100,527 | 100,52 | 100,5235 | 100,639 | 100,644 | 100,6415 | 0,12 | 100,695 | 100,709 | 100,702 | 0,18 |
| 3 | 100,475 | 100,47 | 100,4725 | 100,527 | 100,521 | 100,524 | 100,652 | 100,624 | 100,638 | 0,11 | 100,711 | 100,688 | 100,6995 | 0,17 |
| | | | | | | | Average | | | 0,12 | Average | | | 0,19 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,006 | Standard deviation | | | 0,022 |
| | | | | | | | Std dev/ average (%) | | | 5,207 | Std dev/ average (%) | | | 11,718 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Okay | | | | |

*Table E21: modified AMBT test results of mix C2*

| Date | 23 May 2017 | | | 24 May 2017 | | | 07 June 2017 | | | Linear expansion $(L_n - L_1)/L_o$ | 21 June 2017 | | | Linear expansion $(L_n - L_1)/L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,489 | | | 100,488 | | | 100,491 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,484 | 100,472 | 100,478 | 100,546 | 100,537 | 100,5415 | 100,643 | 100,658 | 100,6505 | 0,11 | 100,67 | 100,685 | 100,6775 | 0,13 |
| 2 | 100,487 | 100,474 | 100,4805 | 100,543 | 100,536 | 100,5395 | 100,665 | 100,658 | 100,6615 | 0,12 | 100,727 | 100,724 | 100,7255 | 0,18 |
| 3 | 100,489 | 100,493 | 100,491 | 100,542 | 100,556 | 100,549 | 100,653 | 100,659 | 100,656 | 0,10 | 100,71 | 100,701 | 100,7055 | 0,15 |
| | | | | | | | Average | | | 0,11 | Average | | | 0,16 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,008 | Standard deviation | | | 0,025 |
| | | | | | | | Std dev/ average (%) | | | 7,427 | Std dev/ average (%) | | | 15,958 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Okay | | | | |

*Table E22: modified AMBT test results of mix C3*

| Date | 20 May 2017 | | | 21 May 2017 | | | 04 June 2017 | | | Linear expansion $(Ln - L_1)/L_0$ | 18 June 2017 | | | Linear expansion $(Ln - L_1)/L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,49 | | | 100,49 | | | 100,49 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,498 | 100,486 | 100,492 | 100,513 | 100,551 | 100,532 | 100,591 | 100,622 | 100,6065 | 0,07 | 100,665 | 100,685 | 100,675 | 0,14 |
| 2 | 100,492 | 100,484 | 100,488 | 100,531 | 100,547 | 100,539 | 100,635 | 100,642 | 100,6385 | 0,10 | 100,694 | 100,69 | 100,692 | 0,15 |
| 3 | 100,475 | 100,484 | 100,4795 | 100,536 | 100,519 | 100,5275 | 100,618 | 100,649 | 100,6335 | 0,11 | 100,658 | 100,705 | 100,6815 | 0,15 |
| | | | | | | | Average | | | 0,09 | Average | | | 0,15 |
| | | | | | | | Reactivity | | | Not reactive | | | | |
| | | | | | | | Standard deviation | | | 0,017 | Standard deviation | | | 0,006 |
| | | | | | | | Std dev/ average (%) | | | 17,819 | Std dev/ average (%) | | | 4,055 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Not okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check D | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E23: modified AMBT test results of mix C4*

| Date | 20 May 2017 | | | 21 May 2017 | | | 04 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_0$ | 18 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,491 | | | 100,489 | | | 100,49 | | | | 100,49 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,478 | 100,477 | 100,4775 | 100,549 | 100,545 | 100,547 | 100,634 | 100,629 | 100,6315 | 0,08 | 100,662 | 100,659 | 100,6605 | 0,11 |
| 2 | 100,484 | 100,469 | 100,4765 | 100,547 | 100,541 | 100,544 | 100,616 | 100,648 | 100,632 | 0,09 | 100,641 | 100,694 | 100,6675 | 0,12 |
| 3 | 100,479 | 100,489 | 100,484 | 100,533 | 100,561 | 100,547 | 100,649 | 100,664 | 100,6565 | 0,11 | 100,676 | 100,661 | 100,6685 | 0,12 |
| | | | | | | | Average | | | 0,09 | Average | | | 0,12 |
| | | | | | | | Reactivity | | | Not reactive | | | | |
| | | | | | | | Standard deviation | | | 0,014 | Standard deviation | | | 0,005 |
| | | | | | | | Std dev/ average (%) | | | 14,556 | Std dev/ average (%) | | | 4,465 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check D | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

*Table E24: modified AMBT test results of mix C5*

| Date | 18 May 2017 | | | 19 May 2017 | | | 02 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_0$ | 16 June 2017 | | | Linear expansion (Ln - $L_1$ )/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,487 | | | 100,49 | | | 100,49 | | | | 100,492 | | | |
| Prism Number | Target placement | | | Zero reading | | | 14 days | | | | 28 days | | | |
| | Li (mm) | | | L0 (mm) | | | L5 (mm) | | | | L6 (mm) | | | |
| | A | B | Average | A | B | Average | A | B | Average | % | A | B | Average | % |
| 1 | 100,493 | 100,488 | 100,4905 | 100,541 | 100,555 | 100,548 | 100,648 | 100,652 | 100,65 | 0,10 | 100,696 | 100,694 | 100,695 | 0,14 |
| 2 | 100,479 | 100,484 | 100,4815 | 100,539 | 100,551 | 100,545 | 100,664 | 100,679 | 100,6715 | 0,13 | 100,753 | 100,764 | 100,7585 | 0,21 |
| 3 | 100,478 | 100,487 | 100,4825 | 100,54 | 100,537 | 100,5385 | 100,651 | 100,625 | 100,638 | 0,10 | 100,69 | 100,649 | 100,6695 | 0,13 |
| | | | | | | | Average | | | 0,11 | Average | | | 0,16 |
| | | | | | | | Reactivity | | | Slowly reactive | | | | |
| | | | | | | | Standard deviation | | | 0,015 | Standard deviation | | | 0,044 |
| | | | | | | | Std dev/ average (%) | | | 13,646 | Std dev/ average (%) | | | 27,034 |
| | | | | | | | Check to choose | | | Check A | | | | |
| | | | | | | SANS 6245 check | Check A | | | Okay | | | | |
| | | | | | | | Check B | | | Not okay | | | | |
| | | | | | | | Check to choose | | | Check C | | | | |
| | | | | | | AAR-2 check | Check C | | | Not okay | | | | |
| | | | | | | | Check D | | | Not okay | | | | |

# Appendix F: detailed compressive strength test results

## F1: detailed compressive strength test results of Phase A mixes

*Table F1: detailed compressive strength test results of Phase A mixes*

| | | Water-cured | | | | | Alkali-cured | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix | Cube no | Mass | Area | Density | Force | Stress | Cube no | Mass | Area | Density | Force | Stress |
| | | g | mm$^2$ | kg/m$^3$ | kN | MPa | | g | mm$^2$ | kg/m$^3$ | kN | MPa |
| A0 | 1 | 291,8 | 2521 | 2303 | 123,8 | 49,1 | 1 | 289,8 | 2551 | 2248 | 104,2 | 40,8 |
| | 2 | 286,4 | 2524 | 2306 | 126,2 | 50,0 | 2 | 284,6 | 2530 | 2272 | 105,9 | 41,9 |
| | 3 | 293,6 | 2542 | 2304 | 136,0 | 53,5 | 3 | 286,9 | 2546 | 2268 | 110,5 | 43,4 |
| | | *Average* | | 2305 | 128,7 | 50,9 | | *Average* | | 2263 | 106,9 | 42,0 |
| | | *Std dev* | | 2 | 6,5 | 2,3 | | *Std dev* | | 12 | 3,3 | 1,3 |
| | | *15% Average* | | - | - | 7,6 | | *15% Average* | | - | - | 6,3 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| A1 | 1 | 298,5 | 2513 | 2333 | 130,0 | 51,7 | 1 | 292,4 | 2538 | 2289 | 124,0 | 48,9 |
| | 2 | 299,1 | 2537 | 2330 | 115,0 | 45,3 | 2 | 291,8 | 2550 | 2243 | 99,0 | 38,8 |
| | 3 | 297,4 | 2524 | 2339 | 130,5 | 51,7 | 3 | 292,5 | 2534 | 2275 | 109,0 | 43,0 |
| | | *Average* | | 2334 | 125,2 | 49,6 | | *Average* | | 2269 | 110,7 | 43,6 |
| | | *Std dev* | | 5 | 8,8 | 3,7 | | *Std dev* | | 24 | 12,6 | 5,0 |
| | | *15% Average* | | - | - | 7,4 | | *15% Average* | | - | - | 6,5 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| A2 | 1 | 293,5 | 2531 | 2325 | 111,5 | 44,1 | 1 | 292,0 | 2535 | 2306 | 116,0 | 45,8 |
| | 2 | 294,0 | 2539 | 2306 | 110,0 | 43,3 | 2 | 287,2 | 2533 | 2269 | 110,0 | 43,4 |
| | 3 | 295,5 | 2523 | 2343 | 118,0 | 46,8 | 3 | 289,8 | 2531 | 2306 | 111,0 | 43,9 |
| | | *Average* | | 2325 | 113,2 | 44,7 | | *Average* | | 2293 | 112,3 | 44,3 |
| | | *Std dev* | | 19 | 4,3 | 1,8 | | *Std dev* | | 21 | 3,2 | 1,2 |
| | | *15% Average* | | - | - | 6,7 | | *15% Average* | | - | - | 6,7 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| A3 | 1 | 296,2 | 2524 | 2375 | 141,0 | 55,9 | 1 | 291,6 | 2561 | 2269 | 113,0 | 44,1 |
| initial | 2 | 289,2 | 2500 | 2329 | 137,0 | 54,8 | 2 | 293,6 | 2561 | 2292 | 116,0 | 45,3 |
| | 3 | 292,5 | 2519 | 2347 | 129,0 | 51,2 | 3 | 291,1 | 2529 | 2278 | 121,0 | 47,8 |
| | | *Average* | | 2350 | 135,7 | 54,0 | | *Average* | | 2280 | 116,7 | 45,8 |
| | | *Std dev* | | 23 | 6,1 | 2,4 | | *Std dev* | | 12 | 4,0 | 1,9 |
| | | *15% Average* | | - | - | 8,1 | | *15% Average* | | - | - | 6,9 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |

*Table F1 continued*

| Water-cured | | | | | | | Alkali-cured | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix | Cube no | Mass | Area | Density | Force | Stress | Cube no | Mass | Area | Density | Force | Stress |
| | | g | mm2 | kg/m3 | kN | MPa | | g | mm2 | kg/m3 | kN | MPa |
| A3 | 1 | 303,8 | 2549 | 2353 | 127,0 | 49,8 | 1 | 293,3 | 2565 | 5249 | 104,5 | 40,7 |
| refined | 2 | 300,1 | 2541 | 2355 | 129,0 | 50,8 | 2 | 289,7 | 2558 | 2202 | 99,0 | 38,7 |
| | 3 | 299,7 | 2517 | 2340 | 131,0 | 52,0 | 3 | 290,8 | 2538 | 2234 | 107,5 | 42,4 |
| | | *Average* | | 2350 | 129,0 | 50,9 | | *Average* | | 3229 | 103,7 | 40,6 |
| | | *Std dev* | | 8 | 2,0 | 1,1 | | *Std dev* | | 1750 | 4,3 | 1,8 |
| | | *15% Average* | | - | - | 7,6 | | *15% Average* | | - | - | 6,1 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| A4 | 1 | 296,5 | 2515 | 2327 | 111,0 | 44,1 | 1 | 295,0 | 2531 | 2306 | 100,0 | 39,5 |
| | 2 | 292,4 | 2519 | 2307 | 109,0 | 43,3 | 2 | 296,7 | 2541 | 2358 | 94,0 | 37,0 |
| | 3 | 299,4 | 2539 | 2333 | 101,0 | 39,8 | 3 | 293,7 | 2528 | 2313 | 103,0 | 40,7 |
| | | *Average* | | 2322 | 107,0 | 42,4 | | *Average* | | 2326 | 99,0 | 39,1 |
| | | *Std dev* | | 14 | 5,3 | 2,3 | | *Std dev* | | 28 | 4,6 | 1,9 |
| | | *15% Average* | | - | - | 6,4 | | *15% Average* | | - | - | 5,9 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| A5 | 1 | 296,9 | 2564 | 2272 | 125,0 | 48,7 | 1 | 294,7 | 2564 | 2255 | 106,0 | 41,3 |
| | 2 | 297,5 | 2536 | 2292 | 121,0 | 47,7 | 2 | 292,6 | 2572 | 2235 | 84,0 | 32,7 |
| | 3 | 294,5 | 2515 | 2311 | 122,0 | 48,5 | 3 | 293,8 | 2562 | 2247 | 94,0 | 36,7 |
| | | *Average* | | 2291 | 122,7 | 48,3 | | *Average* | | 2245 | 94,7 | 36,9 |
| | | *Std dev* | | 20 | 2,1 | 0,5 | | *Std dev* | | 10 | 11,0 | 4,3 |
| | | *15% Average* | | - | - | 7,2 | | *15% Average* | | - | - | 5,5 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| A6 | 1 | 298,7 | 2535 | 2342 | 139,0 | 54,8 | 1 | 293,0 | 2565 | 2304 | 94,0 | 36,6 |
| | 2 | 299,0 | 2534 | 2337 | 134,0 | 52,9 | 2 | 293,8 | 2536 | 2308 | 93,0 | 36,7 |
| | 3 | 297,5 | 2528 | 2365 | 132,0 | 52,2 | 3 | 299,5 | 2563 | 2300 | 91,5 | 35,7 |
| | | *Average* | | 2348 | 135,0 | 53,3 | | *Average* | | 2304 | 92,8 | 36,3 |
| | | *Std dev* | | 15 | 3,6 | 1,4 | | *Std dev* | | 4 | 1,3 | 0,6 |
| | | *15% Average* | | - | - | 8,0 | | *15% Average* | | - | - | 5,5 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |

*Table F1 continued*

| Water-cured | | | | | | | | Alkali-cured | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix | Cube no | Mass | Area | Density | Force | Stress | | Cube no | Mass | Area | Density | Force | Stress |
| | | g | mm2 | kg/m3 | kN | MPa | | | g | mm2 | kg/m3 | kN | MPa |
| A7 | 1 | 293,2 | 2518 | 2359 | 163,0 | 64,7 | | 1 | 290,4 | 2553 | 2262 | 116,0 | 45,4 |
| initial | 2 | 298,3 | 2542 | 2324 | 162,0 | 63,7 | | 2 | 290,5 | 2556 | 2304 | 128,0 | 50,1 |
| | 3 | 295,3 | 2539 | 2355 | 167,0 | 65,8 | | 3 | 291,9 | 2552 | 2283 | 122,0 | 47,8 |
| | | *Average* | | 2346 | 164,0 | 64,7 | | | *Average* | | 2283 | 122,0 | 47,8 |
| | | *Std dev* | | 19 | 2,6 | 1,0 | | | *Std dev* | | 21 | 6,0 | 2,3 |
| | | *15% Average* | | - | - | 9,7 | | | *15% Average* | | - | - | 7,2 |
| | | *Check maximum* | | - | - | Okay | | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | | *Check minimum* | | - | - | OKay |
| A7 | 1 | 297,3 | 2528 | 2328 | 119,0 | 47,1 | | 1 | 291,5 | 2564 | 2252 | 100,5 | 39,2 |
| refined | 2 | 292,9 | 2513 | 2361 | 126,0 | 50,1 | | 2 | 297,6 | 2550 | 2285 | 99,0 | 38,8 |
| | 3 | 293,5 | 2518 | 2315 | 125,0 | 49,6 | | 3 | 295,7 | 2558 | 2265 | 100,0 | 39,1 |
| | | *Average* | | 2335 | 123,3 | 49,0 | | | *Average* | | 2267 | 99,8 | 39,0 |
| | | *Std dev* | | 24 | 3,8 | 1,6 | | | *Std dev* | | 17 | 0,8 | 0,2 |
| | | *15% Average* | | - | - | 7,3 | | | *15% Average* | | - | - | 5,9 |
| | | *Check maximum* | | - | - | Okay | | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | | *Check minimum* | | - | - | OKay |
| A8 | 1 | 297,1 | 2501 | 2379 | 135,0 | 54,0 | | 1 | 295,9 | 2544 | 2321 | 109,0 | 42,8 |
| | 2 | 299,8 | 2525 | 2343 | 124,0 | 49,1 | | 2 | 295,7 | 2555 | 2305 | 110,0 | 43,0 |
| | 3 | 292,8 | 2507 | 2353 | 137,0 | 54,6 | | 3 | 298,6 | 2555 | 2280 | 108,0 | 42,3 |
| | | *Average* | | 2358 | 132,0 | 52,6 | | | *Average* | | 2302 | 109,0 | 42,7 |
| | | *Std dev* | | 19 | 7,0 | 3,0 | | | *Std dev* | | 21 | 1,0 | 0,4 |
| | | *15% Average* | | - | - | 7,9 | | | *15% Average* | | - | - | 6,4 |
| | | *Check maximum* | | - | - | Okay | | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | | *Check minimum* | | - | - | OKay |
| A9 | 1 | 294,9 | 2526 | 2339 | 140,4 | 55,6 | | 1 | 294,1 | 2535 | 2319 | 122,0 | 48,1 |
| | 2 | 294,8 | 2540 | 2344 | 138,5 | 54,5 | | 2 | 294,2 | 2542 | 2300 | 119,5 | 47,0 |
| | 3 | 298,9 | 2540 | 2345 | 135,0 | 53,1 | | 3 | 289,8 | 2541 | 2294 | 117,0 | 46,0 |
| | | *Average* | | 2342 | 138,0 | 54,4 | | | *Average* | | 2304 | 119,5 | 47,1 |
| | | *Std dev* | | 3 | 2,7 | 1,2 | | | *Std dev* | | 13 | 2,5 | 1,0 |
| | | *15% Average* | | - | - | 8,2 | | | *15% Average* | | - | - | 7,1 |
| | | *Check maximum* | | - | - | Okay | | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | | *Check minimum* | | - | - | OKay |

## F2: detailed compressive strength test results of Stage 1 – Phase B and C

*Table F2: detailed compressive strength test results of Phase B and C*

| | | Water-cured | | | | | Alkali-cured | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix | Cube no | Mass | Area | Density | Force | Stress | Cube no | Mass | Area | Density | Force | Stress |
| | | g | mm2 | kg/m3 | kN | MPa | | g | mm2 | kg/m3 | kN | MPa |
| B1 | 1 | 303,8 | 2537 | 2366 | 134,0 | 52,8 | 1 | 299,1 | 2518 | 2332 | 127,0 | 50,4 |
| | 2 | 297,8 | 2521 | 2343 | 129,0 | 51,2 | 2 | 302,6 | 2531 | 2311 | 135,0 | 53,3 |
| | 3 | 300,7 | 2508 | 2348 | 109,0 | 43,5 | 3 | 294,6 | 2519 | 2304 | 145,0 | 57,6 |
| | | *Average* | | 2352 | 124,0 | 49,1 | | *Average* | | 2315 | 135,7 | 53,8 |
| | | *Std dev* | | 12 | 13,2 | 5,0 | | *Std dev* | | 15 | 9,0 | 3,6 |
| | | *15% Average* | | - | - | 7,4 | | *15% Average* | | - | - | 8,1 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| B2 | 1 | 301,7 | 2522 | 2339 | 113,0 | 44,8 | 1 | 291,9 | 2550 | 2245 | 128,0 | 50,2 |
| | 2 | 300,2 | 2541 | 2310 | 117,0 | 46,1 | 2 | 298,4 | 2529 | 2300 | 131,0 | 51,8 |
| | 3 | 300,6 | 2540 | 2320 | 104,0 | 41,0 | 3 | 300,0 | 2538 | 2307 | 129,0 | 50,8 |
| | | *Average* | | 2323 | 111,3 | 43,9 | | *Average* | | 2284 | 129,3 | 50,9 |
| | | *Std dev* | | 15 | 6,7 | 2,7 | | *Std dev* | | 34 | 1,5 | 0,8 |
| | | *15% Average* | | - | - | 6,6 | | *15% Average* | | - | - | 7,6 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| B3 | 1 | 298,1 | 2521 | 2331 | 114,0 | 45,2 | 1 | 299,2 | 2531 | 2327 | 115,0 | 45,4 |
| | 2 | 297,0 | 2532 | 2286 | 117,0 | 46,2 | 2 | 296,8 | 2525 | 2300 | 113,0 | 44,8 |
| | 3 | 298,0 | 2520 | 2313 | 114,5 | 45,4 | 3 | 295,9 | 2523 | 2282 | 118,0 | 46,8 |
| | | *Average* | | 2310 | 115,2 | 45,6 | | *Average* | | 2303 | 115,3 | 45,7 |
| | | *Std dev* | | 23 | 1,6 | 0,5 | | *Std dev* | | 23 | 2,5 | 1,0 |
| | | *15% Average* | | - | - | 6,8 | | *15% Average* | | - | - | 6,8 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| B4 | 1 | 300,4 | 2546 | 2336 | 107,0 | 42,0 | 1 | 299,2 | 2541 | 2285 | 122,0 | 48,0 |
| | 2 | 298,3 | 2526 | 2331 | 99,0 | 39,2 | 2 | 299,0 | 2532 | 2303 | 131,0 | 51,7 |
| | 3 | 299,4 | 2528 | 2348 | 107,0 | 42,3 | 3 | 295,6 | 2546 | 2292 | 128,0 | 50,3 |
| | | *Average* | | 2339 | 104,3 | 41,2 | | *Average* | | 2293 | 127,0 | 50,0 |
| | | *Std dev* | | 9 | 4,6 | 1,7 | | *Std dev* | | 9 | 4,6 | 1,9 |
| | | *15% Average* | | - | - | 6,2 | | *15% Average* | | - | - | 7,5 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |

*Table F2 continued*

| | | Water-cured | | | | | Alkali-cured | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix | Cube no | Mass<br>g | Area<br>mm2 | Density<br>kg/m3 | Force<br>kN | Stress<br>MPa | Cube no | Mass<br>g | Area<br>mm2 | Density<br>kg/m3 | Force<br>kN | Stress<br>MPa |
| B5 | 1 | 284,4 | 2526 | 2281 | 99,0 | 39,2 | 1 | 290,7 | 2542 | 2276 | 110,0 | 43,3 |
| | 2 | 291,7 | 2516 | 2290 | 98,0 | 39,0 | 2 | 288,6 | 2520 | 2288 | 102,0 | 40,5 |
| | 3 | 290,6 | 2510 | 2316 | 102,0 | 40,6 | 3 | 287,1 | 2533 | 2270 | 107,0 | 42,2 |
| | | *Average* | | 2295 | 99,7 | 39,6 | | *Average* | | 2278 | 106,3 | 42,0 |
| | | *Std dev* | | 18 | 2,1 | 0,9 | | *Std dev* | | 9 | 4,0 | 1,4 |
| | | *15% Average* | | - | - | 5,9 | | *15% Average* | | - | - | 6,3 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| B6 | 1 | 290,1 | 2504 | 2304 | 90,0 | 35,9 | 1 | 284,8 | 2527 | 2264 | 100,0 | 39,6 |
| | 2 | 290,6 | 2512 | 2340 | 88,0 | 35,0 | 2 | 291,7 | 2556 | 2309 | 86,0 | 33,6 |
| | 3 | 290,2 | 2500 | 2318 | 86,0 | 34,4 | 3 | 286,7 | 2507 | 2288 | 97,0 | 38,7 |
| | | *Average* | | 2320 | 88,0 | 35,1 | | *Average* | | 2287 | 94,3 | 37,3 |
| | | *Std dev* | | 18 | 2,0 | 0,8 | | *Std dev* | | 23 | 7,4 | 3,2 |
| | | *15% Average* | | - | - | 5,3 | | *15% Average* | | - | - | 5,6 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| C1 | 1 | 294,1 | 2506 | 2346 | 90,0 | 35,9 | 1 | 293,4 | 2520 | 2294 | 100,0 | 39,7 |
| | 2 | 291,4 | 2513 | 2304 | 94,0 | 37,4 | 2 | 287,2 | 2544 | 2265 | 106,0 | 41,7 |
| | 3 | 294,3 | 2493 | 2355 | 99,0 | 39,7 | 3 | 294,6 | 2544 | 2310 | 98,0 | 38,5 |
| | | *Average* | | 2335 | 94,3 | 37,7 | | *Average* | | 2290 | 101,3 | 40,0 |
| | | *Std dev* | | 27 | 4,5 | 1,9 | | *Std dev* | | 23 | 4,2 | 1,6 |
| | | *15% Average* | | - | - | 5,7 | | *15% Average* | | - | - | 6,0 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| C2 | 1 | 291,9 | 2526 | 2281 | 81,0 | 32,1 | 1 | 289,4 | 2559 | 2238 | 85,0 | 33,2 |
| | 2 | 294,0 | 2508 | 2324 | 80,0 | 31,9 | 2 | 285,4 | 2536 | 2257 | 86,0 | 33,9 |
| | 3 | 291,7 | 2504 | 2262 | 82,0 | 32,7 | 3 | 287,6 | 2542 | 2255 | 85,0 | 33,4 |
| | | *Average* | | 2289 | 81,0 | 32,2 | | *Average* | | 2250 | 85,3 | 33,5 |
| | | *Std dev* | | 31 | 1,0 | 0,5 | | *Std dev* | | 10 | 0,6 | 0,4 |
| | | *15% Average* | | - | - | 4,8 | | *15% Average* | | - | - | 5,0 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |

*Table F2 continued*

| | | Water-cured | | | | | Alkali-cured | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix | Cube no | Mass | Area | Density | Force | Stress | Cube no | Mass | Area | Density | Force | Stress |
| | | g | mm2 | kg/m3 | kN | MPa | | g | mm2 | kg/m3 | kN | MPa |
| C3 | 1 | 292,2 | 2522 | 2331 | 74,0 | 29,3 | 1 | 287,2 | 2513 | 2250 | 76,0 | 30,2 |
| | 2 | 292,4 | 2492 | 2359 | 70,0 | 28,1 | 2 | 289,5 | 2505 | 2299 | 80,0 | 31,9 |
| | 3 | 289,3 | 2533 | 2288 | 71,0 | 28,0 | 3 | 294,5 | 2536 | 2301 | 75,0 | 29,6 |
| | | *Average* | | 2326 | 71,7 | 28,5 | | *Average* | | 2283 | 77,0 | 30,6 |
| | | *Std dev* | | 36 | 2,1 | 0,7 | | *Std dev* | | 29 | 2,6 | 1,2 |
| | | *15% Average* | | - | - | 4,3 | | *15% Average* | | - | - | 4,6 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| C4 | 1 | 291,9 | 2539 | 2293 | 54,0 | 21,3 | 1 | 285,0 | 2522 | 2271 | 65,0 | 25,8 |
| | 2 | 295,3 | 2522 | 2282 | 51,0 | 20,2 | 2 | 292,9 | 2522 | 2282 | 61,0 | 24,2 |
| | 3 | 292,9 | 2559 | 2301 | 55,0 | 21,5 | 3 | 287,9 | 2498 | 2255 | 57,0 | 22,8 |
| | | *Average* | | 2292 | 53,3 | 21,0 | | *Average* | | 2269 | 61,0 | 24,3 |
| | | *Std dev* | | 10 | 2,1 | 0,7 | | *Std dev* | | 14 | 4,0 | 1,5 |
| | | *15% Average* | | - | - | 3,1 | | *15% Average* | | - | - | 3,6 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |
| C5 | 1 | 286,1 | 2083 | 2745 | 40,0 | 19,2 | 1 | 281,6 | 2529 | 2247 | 50,0 | 19,8 |
| | 2 | 291,6 | 2507 | 2274 | 40,0 | 16,0 | 2 | 289,1 | 2542 | 2211 | 55,0 | 21,6 |
| | 3 | 289,4 | 2529 | 2243 | 38,5 | 15,2 | 3 | 287,4 | 2524 | 2227 | 54,0 | 21,4 |
| | | *Average* | | 2421 | 39,5 | 16,8 | | *Average* | | 2228 | 53,0 | 20,9 |
| | | *Std dev* | | 281 | 0,9 | 2,1 | | *Std dev* | | 18 | 2,6 | 1,0 |
| | | *15% Average* | | - | - | 2,5 | | *15% Average* | | - | - | 3,1 |
| | | *Check maximum* | | - | - | Okay | | *Check maximum* | | - | - | Okay |
| | | *Check minimum* | | - | - | OKay | | *Check minimum* | | - | - | OKay |

# Appendix G: detailed subsidiary test results

The results of the light microscopy, electron microscopy and EDS are discussed in Chapter 4.4. Raw data of the tests can be requested to the author if required.

## Calculations of alkali concentration in mixes

For benchmarking purposes, with respect to the results of the ICP-OES test, the total concentration of alkalis in the cement had to be calculated. This appendix discusses the calculations. Firstly, the mass of alkali oxides, in the CEM II A/L 52.5N in each mix had to be calculated based on the sodium oxide content of, 0.24%, and potassium oxide content, 0.72% per cubic metre. The mass of alkali oxides in three 50×50×50mm cubes, the amount of concrete used for pore expression, were calculated. Based on the molar masses of the of the alkali oxides, the respective masses of alkalis were calculated, refer to Table G1. The amount of mass of sodium in the sodium hydroxide used to boost the alkali in the mixes was then added to calculate the final total concentrations of alkalis in the mixes, refer to Table G2. Finally the mass is calculated per litre based on the volume of the cubes used.

*Table G1: calculated masses of alkalis from CEM II A/L 52.5N*

| Mix No | Mass in three 50mm cubes (mg) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cement | Extender | Total | $Na_2O$ | $K_2O$ | Na | K |
| A0 | 232087,50 | 0,00 | 232087,50 | 557,01 | 1671,03 | 412,80 | 1306,75 |
| A5 | 232087,50 | 0,00 | 232087,50 | 557,01 | 1671,03 | 412,80 | 1306,75 |
| C1 | 183937,50 | 45975,00 | 229912,50 | 441,45 | 1324,35 | 327,16 | 1035,64 |
| C4 | 113850,00 | 113850,00 | 227700,00 | 273,24 | 819,72 | 202,50 | 641,02 |

*Table G2: calculated total concentration of alkalis in each mix*

| Mix No | Mass from cement (mg) | | Na (mg) from alkali boost | Total | | Concentration (mg/L) | |
|---|---|---|---|---|---|---|---|
| | Na | K | | Na | K | Na | K |
| A0 | 412,80 | 1306,75 | 512,24 | 925,04 | 1306,75 | 2466,77 | 3484,65 |
| A5 | 412,80 | 1306,75 | 514,39 | 927,19 | 1306,75 | 2472,51 | 3484,65 |
| C1 | 327,16 | 1035,64 | 408,93 | 736,09 | 1035,64 | 1962,90 | 2761,71 |
| C4 | 202,50 | 641,02 | 253,97 | 456,46 | 641,02 | 1217,24 | 1709,39 |

# Appendix H: detailed long-term performance test results

Two long-term performance tests were performed on the concrete specimens. Appendix H1 presents the detailed results of the modified AAR-4 test while Appendix H2 presents the results of the field testing available at the time of writing. It is to be noted that both test will be continued beyond the period of this dissertation.

## H1: detailed modified AAR-4 test results

*Table H1: modified AAR-4 results of mix D1*

| Date | 21 September 2017 | | | 26 October 2017 | | | Linear expansion (Ln - $L_1$)/$L_0$ | 16 November 2017 | | | Linear expansion (Ln - $L_1$)/$L_0$ | 04 January 2018 | | | Linear expansion (Ln - $L_1$)/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,527 | | | 100,484 | | | | 100,49 | | | | 100,487 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,528 | 100,525 | 100,5265 | 100,474 | 100,462 | 100,468 | -0,02 | 100,478 | 100,467 | 100,4725 | -0,02 | 100,477 | 100,463 | 100,47 | -0,02 |
| 2 | 100,517 | 100,527 | 100,522 | 100,459 | 100,469 | 100,464 | -0,01 | 100,465 | 100,471 | 100,468 | -0,02 | 100,463 | 100,481 | 100,472 | -0,01 |
| 3 | 100,531 | 100,528 | 100,5295 | 100,479 | 100,466 | 100,4725 | -0,01 | 100,479 | 100,47 | 100,4745 | -0,02 | 100,481 | 100,468 | 100,4745 | -0,02 |
| | | | | | Average | | -0,01 | | Average | | -0,02 | | Average | | -0,01 |

*Table H2: modified AAR-4 test results of mix D2*

| Date | 26 September 2017 | | | 31 October 2017 | | | Linear expansion (Ln - $L_1$)/$L_0$ | 21 November 2017 | | | Linear expansion (Ln - $L_1$)/$L_0$ | 09 January 2018 | | | Linear expansion (Ln - $L_1$)/$L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,471 | | | 100,483 | | | | 100,488 | | | | 100,486 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,474 | 100,472 | 100,473 | 100,472 | 100,466 | 100,469 | -0,02 | 100,48 | 100,469 | 100,4745 | -0,02 | 100,478 | 100,471 | 100,4745 | -0,01 |
| 2 | 100,469 | 100,47 | 100,4695 | 100,463 | 100,466 | 100,4645 | -0,02 | 100,464 | 100,435 | 100,4495 | -0,04 | 100,468 | 100,469 | 100,4685 | -0,02 |
| 3 | 100,444 | 100,441 | 100,4425 | 100,432 | 100,446 | 100,439 | -0,02 | 100,466 | 100,452 | 100,459 | 0,00 | 100,43 | 100,451 | 100,4405 | -0,02 |
| | | | | | Average | | -0,02 | | Average | | -0,02 | | Average | | -0,02 |

*Table H3: modified AAR-4 test results of mix D3*

| Date | 05 October 2017 | | | 09 November 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 30 November 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 18 January 2018 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,49 | | | 100,49 | | | | 100,488 | | | | 100,485 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,448 | 100,486 | 100,467 | 100,463 | 100,471 | 100,467 | 0,00 | 100,456 | 100,462 | 100,459 | -0,01 | 100,477 | 100,485 | 100,481 | 0,02 |
| 2 | 100,39 | 100,479 | 100,4345 | 100,353 | 100,466 | 100,4095 | -0,03 | 100,407 | 100,468 | 100,4375 | 0,00 | 100,405 | 100,467 | 100,436 | 0,01 |
| 3 | 100,451 | 100,501 | 100,476 | 100,395 | 100,491 | 100,443 | -0,03 | 100,44 | 100,477 | 100,4585 | -0,02 | 100,401 | 100,491 | 100,446 | -0,03 |
| | | | | | Average | | -0,02 | | Average | | -0,01 | | Average | | 0,00 |

*Table H4: modified AAR-4 test results of mix D4*

| Date | 26 September 2017 | | | 31 October 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 21 November 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 09 January 2018 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,466 | | | 100,483 | | | | 100,488 | | | | 100,485 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,47 | 100,462 | 100,466 | 100,462 | 100,468 | 100,465 | -0,02 | 100,465 | 100,474 | 100,4695 | -0,02 | 100,464 | 100,468 | 100,466 | -0,02 |
| 2 | 100,489 | 100,372 | 100,4305 | 100,488 | 100,386 | 100,437 | -0,01 | 100,488 | 100,382 | 100,435 | -0,02 | 100,49 | 100,372 | 100,431 | -0,02 |
| 3 | 100,453 | 100,458 | 100,4555 | 100,45 | 100,464 | 100,457 | -0,02 | 100,453 | 100,464 | 100,4585 | -0,02 | 100,456 | 100,466 | 100,461 | -0,01 |
| | | | | | Average | | -0,01 | | Average | | -0,02 | | Average | | -0,02 |

*Table H5: modified AAR-4 test results of mix D5*

| Date | 05 October 2017 | | | 09 November 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 30 November 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 18 January 2018 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,487 | | | 100,488 | | | | 100,49 | | | | 100,486 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,47 | 100,464 | 100,467 | 100,472 | 100,454 | 100,463 | -0,01 | 100,466 | 100,45 | 100,458 | -0,01 | 100,471 | 100,45 | 100,4605 | -0,01 |
| 2 | 100,481 | 100,478 | 100,4795 | 100,468 | 100,475 | 100,4715 | -0,01 | 100,467 | 100,471 | 100,469 | -0,01 | 100,471 | 100,476 | 100,4735 | -0,01 |
| 3 | 100,455 | 100,523 | 100,489 | 100,442 | 100,489 | 100,4655 | -0,02 | 100,438 | 100,524 | 100,481 | -0,01 | 100,445 | 100,461 | 100,453 | -0,04 |
| | | | | | Average | | -0,01 | | Average | | -0,01 | | Average | | -0,02 |

## H2: detailed field testing results

*Table H6: field testing results of mix D1*

| Date | 21 September 2017 | | | 26 October 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 16 November 2017 | | | Linear expansion (Ln - $L_1$ )/$L_o$ | 04 January 2018 | | | Linear expansion (Ln - $L_1$ )/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,49 | | | 100,489 | | | | 100,491 | | | | 100,486 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,492 | 100,458 | 100,475 | 100,484 | 100,481 | 100,4825 | 0,01 | 100,492 | 100,478 | 100,485 | 0,01 | 100,49 | 100,458 | 100,474 | 0,00 |
| 2 | 100,471 | 100,495 | 100,483 | 100,475 | 100,503 | 100,489 | 0,01 | 100,467 | 100,473 | 100,47 | -0,01 | 100,47 | 100,456 | 100,463 | -0,02 |
| 3 | 100,466 | 100,496 | 100,481 | 100,49 | 100,484 | 100,487 | 0,01 | 100,471 | 100,479 | 100,475 | -0,01 | 100,465 | 100,472 | 100,4685 | -0,01 |
| | | | | | Average | | 0,01 | | Average | | 0,00 | | Average | | -0,01 |

*Table H7: field testing results of mix D2*

| Date | 26 September 2017 | | | 31 October 2017 | | | Linear expansion $(Ln - L_1)/L_0$ | 21 November 2017 | | | Linear expansion $(Ln - L_1)/L_0$ | 09 January 2018 | | | Linear expansion $(Ln - L_1)/L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,471 | | | 100,483 | | | | 100,488 | | | | 100,489 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,481 | 100,465 | 100,473 | 100,432 | 100,478 | 100,455 | -0,03 | 100,48 | 100,465 | 100,4725 | -0,02 | 100,47 | 100,464 | 100,467 | -0,02 |
| 2 | 100,464 | 100,467 | 100,4655 | 100,459 | 100,441 | 100,45 | -0,03 | 100,458 | 100,459 | 100,4585 | -0,02 | 100,451 | 100,455 | 100,453 | -0,03 |
| 3 | 100,421 | 100,465 | 100,443 | 100,467 | 100,428 | 100,4475 | -0,01 | 100,417 | 100,461 | 100,439 | -0,02 | 100,411 | 100,457 | 100,434 | -0,03 |
| | | | | | Average | | -0,02 | | Average | | -0,02 | | Average | | -0,03 |

*Table H8: field testing results of mix D3*

| Date | 05 October 2017 | | | 09 November 2017 | | | Linear expansion $(Ln - L_1)/L_0$ | 30 November 2017 | | | Linear expansion $(Ln - L_1)/L_0$ | 18 January 2018 | | | Linear expansion $(Ln - L_1)/L_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,486 | | | 100,49 | | | | 100,488 | | | | 100,489 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,455 | 100,483 | 100,469 | 100,462 | 100,477 | 100,4695 | 0,00 | 100,451 | 100,475 | 100,463 | -0,01 | 100,435 | 100,465 | 100,45 | -0,02 |
| 2 | 100,48 | 100,48 | 100,48 | 100,473 | 100,479 | 100,476 | -0,01 | 100,472 | 100,478 | 100,475 | -0,01 | 100,461 | 100,465 | 100,463 | -0,02 |
| 3 | 100,468 | 100,632 | 100,55 | 100,463 | 100,6587 | 100,5609 | 0,01 | 100,458 | 100,652 | 100,555 | 0,00 | 100,449 | 100,575 | 100,512 | -0,04 |
| | | | | | Average | | 0,00 | | Average | | 0,00 | | Average | | -0,03 |

*Table H9: field testing of mix D4*

| Date | 26 September 2017 | | | 31 October 2017 | | | Linear expansion (Ln - $L_1$)/$L_o$ | 21 November 2017 | | | Linear expansion (Ln - $L_1$)/$L_o$ | 09 January 2018 | | | Linear expansion (Ln - $L_1$)/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,466 | | | 100,483 | | | | 100,488 | | | | 100,485 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,474 | 100,354 | 100,414 | 100,486 | 100,474 | 100,48 | 0,05 | 100,479 | 100,388 | 100,4335 | 0,00 | 100,478 | 100,375 | 100,4265 | -0,01 |
| 2 | 100,463 | 100,469 | 100,466 | 100,469 | 100,479 | 100,474 | -0,01 | 100,466 | 100,467 | 100,4665 | -0,02 | 100,465 | 100,455 | 100,46 | -0,02 |
| 3 | 100,503 | 100,357 | 100,43 | 100,504 | 100,366 | 100,435 | -0,01 | 100,497 | 100,358 | 100,4275 | -0,02 | 100,491 | 100,372 | 100,4315 | -0,02 |
| | | | | | Average | | 0,01 | | Average | | -0,02 | | Average | | -0,02 |

*Table H10: field testing of mix D5*

| Date | 05 October 2017 | | | 09 November 2017 | | | Linear expansion (Ln - $L_1$)/$L_o$ | 30 November 2017 | | | Linear expansion (Ln - $L_1$)/$L_o$ | 18 January 2018 | | | Linear expansion (Ln - $L_1$)/$L_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration reading | 100,49 | | | 100,488 | | | | 100,488 | | | | 100,485 | | | |
| Prism Number | Zero reading | | | 5 weeks | | | | 8 weeks | | | | 15 weeks | | | |
| | L0 (mm) | | | L1 (mm) | | | | L2 (mm) | | | | L4 (mm) | | | |
| | A | B | Average | A | B | Average | % | A | B | Average | % | A | B | Average | % |
| 1 | 100,448 | 100,481 | 100,4645 | 100,458 | 100,476 | 100,467 | 0,00 | 100,424 | 100,476 | 100,45 | -0,01 | 100,412 | 100,463 | 100,4375 | -0,02 |
| 2 | 100,471 | 100,457 | 100,464 | 100,459 | 100,434 | 100,4465 | -0,02 | 100,448 | 100,44 | 100,444 | -0,02 | 100,444 | 100,428 | 100,436 | -0,02 |
| 3 | 100,463 | 100,414 | 100,4385 | 100,466 | 100,41 | 100,438 | 0,00 | 100,466 | 100,41 | 100,438 | 0,00 | 100,445 | 100,416 | 100,4305 | 0,00 |
| | | | | | Average | | 0,00 | | Average | | -0,01 | | Average | | -0,02 |