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UNIVERSITY OF CAPE TOWN
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FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

Department of Civil Engineering

INVESTIGATING REPAIR MORTARS CONTAINING SUPERABSORBENT POLYMERS AS A METHOD OF INTERNAL CURING TO IMPROVE CONCRETE PATCH REPAIR PERFORMANCE

University of Cape Town

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Date: 5 October 2012

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 Civil Engineering

CoMSIRU	Concrete Materials and Structural Integrity Research Unit
National Research Foundation NRF	The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.

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ABSTRACT

Concrete structures are designed with a specific service life in mind and deteriorate over time due to their exposure to environmental conditions. In order to increase the service life of concrete structures, they can sometimes be rehabilitated and repaired using concrete overlays. However, problems may develop between the new and old concrete due to differential shrinkage between the concrete substrate and overlay. These differential shrinkages typically result in the build-up of tensile stresses within the overlay. If the concrete does not possess sufficient tensile strength, the overlay will crack and or delaminate, which is usually considered failure.

To prevent cracking, the quantity of shrinkage that occurs in the overlay needs to be minimised. Literature suggests that the addition of superabsorbent polymers (SAP's) to the concrete overlay can reduce the total shrinkage that occurs. A large amount of research exists pertaining to the use on SAP's in high performance concrete (HPC), while very little research has been done regarding their influence of overlays. This research investigated how the addition of SAP's to overlays containing silica fume (SF) would improve bonded concrete overlay performance.

Testing was conducted on overlay samples with a water:binder (W/b) ratio of 0.45 and 0.55 with SAP contents of containing 0%, 0.2%, 0.4% and 0.6% of the total binder content. Samples were subjected to a large number of tests including compressive, tensile and shear bond strength, durability, tensile relaxation, elastic modulus, carbonation, bulk diffusion and free and restrained shrinkage.

The results of this research indicated that the SAP's had a greater influence on samples with a higher w/b ratio. The results also suggested that an increase in SAP content resulted in improved tensile strength, tensile relaxation and durability while also reducing the rate of drying shrinkage at early ages. This indicated that SAP's can be used in mix design to improve bonded concrete overlay performance.

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University of Cape Town

TABLE OF CONTENTS

University of Cape Town

University of Cape Town

University of Cape Town

University of Cape Town

LIST OF FIGURES

University of Cape Town

University of Cape Town

University of Cape Town

LIST OF TABLES

University of Cape Town

1. INTRODUCTION

1.1 Background and problem statement

Concrete structures are designed with a specific service life in mind and deteriorate over time due to their exposure to environmental conditions. Service life can be defined as the life expectancy of a structure as per its use. In order to increase the service life of concrete structures, they can be reconstructed, rehabilitated and repaired. Repair methods are often favoured as opposed to reconstruction as they may be less costly and time consuming. Usually, the selection of effective repair techniques involves striking a balance between costs, suitability to the level of deterioration of the structure and efficiency of repair after it has been implemented (Schrader, 1992).

Repairs and retrofitting concrete structures are done for a number of reasons. In areas where the steel reinforcement has corroded, patch repairs are required. Patch repairs involve the removal of the damaged concrete and steel and replacing it with new steel and fresh concrete. By following the correct techniques, the structure can be restored to its original condition.

Casting concrete overlays onto an existing, deteriorated surface is a popular form of rehabilitation. Bonded concrete overlays may be applied over concrete substrates to increase service-life, for surface protection and to improve aesthetic appearance. They are primarily used in rehabilitation and retrofitting projects after the removal of distressed surface layer (Indrajit *et al*, 2005). The substrate surface is prepared such that whenever a fresh overlay is applied, it adheres to the substrate and a bond is formed. Figure 1.1 shows the overlay, substrate and the line of contact between the two layers, called the interface or bond line.

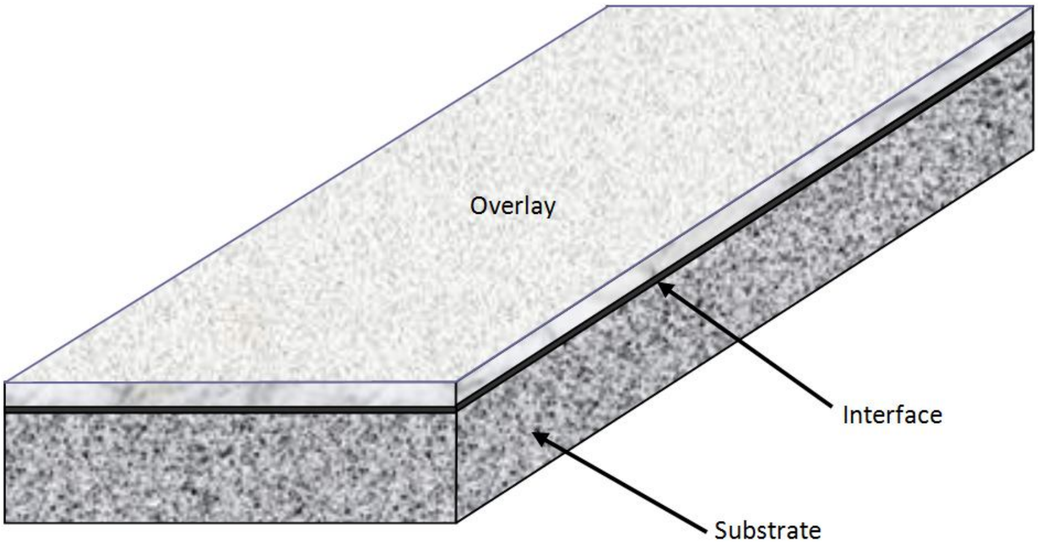

Figure 1-1: Bonded concrete overlay (Masuku, 2009)

The bond formed at the interface creates a boundary condition in the composite section. Provided full bond is assumed, overlay and substrate volume changes at the interface are the same (Beushausen, 2005). Components of this composite system respond differently to different environmental conditions. If the components are analysed individually, it is clear that the overlay, relatively younger than the substrate, undergoes more changes in response to the environment than the substrate.

The younger overlay undergoes larger volumetric changes when compared to the older substrate. The driving force behind the volume change in the overlay is shrinkage. Environmental and internal effects cause the overlay to undergo shrinkage whilst substrate shrinkage is negligible. Shrinkage mainly involves loss of moisture to the environment as well as to hydration. This differential shrinkage results in the build-up of interface shear stresses and direct stresses in the composites. These consist mainly of tensile stresses in the overlay. If the overlay does not have sufficient tensile strength to resist the tensile stresses that develop, the overlay will crack. Cracking of bonded concrete overlays is considered failure as the overlay will no longer perform its primary function of improving aesthetics and providing a barrier to aggressive agents entering the overlay causing corrosion of the steel reinforcing.

Mitigation of shrinkage will greatly improve bonded concrete overlay performance. Literature suggests that the addition of superabsorbent polymers (SAP's) can reduce autogenous shrinkage in high performance concrete. Literature also suggests that the addition of SAP's can improve concrete tensile strength, which is an important concrete overlay characteristic. However, very little literature is available regarding the influence of SAP's on other important overlay properties such as durability, tensile relaxation and bond strength.

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1.2 Motivation for Research

Research conducted by Igarshi & Watanabe (2006), van der Ham *et al*. (2007), Lam (2005) Kovler & Jensen, (2006) and Kolver & Jensen (2007) suggests that the addition of SAP's can reduce shrinkage. Jensen & Hanson (2001) suggest that the addition of SAP's can reduce, if not prevent, autogenous shrinkage if a sufficient quantity of SAP is used. Literature suggests that similar quantities of total shrinkage are observed in samples containing SAP's and their equivalent control mixes. However, the addition of SAP's reduces the rate at which shrinkage occurs. This is especially important in bonded concrete overlays, where early age shrinkage is the driving force behind overlay cracking. Shrinkage results in the built up tensile stresses within the overlay. Mitigating the quantity of early age shrinkage will reduce the likelihood of overlays cracking as it will allow sufficient tensile strength development to overcome the tensile stresses. If sufficient shrinkage reduction can be achieved, then cracking, debonding and ultimately failure of bonded concrete overlays may be avoided.

Insufficient research is available on the influence of SAP's on other important overlay properties as well as their influence on various cement extenders. Little research is available on the impact of SAP's on tensile relaxation, carbonation and chloride resistance, bond strength, elastic modulus, while contrasting views exist relating to the influence of SAP's on compressive strength of concrete. The use of SAP's in bonded concrete overlays had not been investigated and this author believes that the addition of SAP's can improve overlay performance.

1.3 Aim of research

This research investigates the influence that different quantities of SAP's will have on the performance of bonded concrete overlays. The impact of the addition of SAP's on compressive strength, tensile strength, carbonation resistance, chloride resistance, porosity, total shrinkage, restrained shrinkage, bond strength and tensile relaxation will be investigated.

1.4 Hypothesis

This research proposes that the addition of SAP's can reduce the quantity and rate of shrinkage that occurs within bonded concrete overlays. The addition of SAP's can potentially improve the microstructure of the cement past, which could improve compressive and tensile strength as well as durability properties. These improvements in concrete overlay properties will reduce the likelihood of overlay failure and will improve overlay performance.

1.5 Research objectives

To ensure that an overlay system remains durable and fully functioning during the intended service life, it is important to arrest overlay cracking and to prevent delamination (Carlswärd, 2006). Due to the unknown impact SAP's will have on the performance of various cement extenders, a wide variety of tests need to be performed. Therefore an analytical approach is needed to clearly show the impact SAP's will have on the main factors affecting bonded concrete overlays. Important characteristics of overlay properties will be determined by performing specific tests. In this regard, the objectives of this research are to determine the influence of SAP's on:

- Compressive strength
- Tensile strength
- Carbonation resistance
- Chloride resistance
- Porosity
- Total shrinkage
- Restrained shrinkage
- Tensile relaxation
- Bond strength
- Elastic modulus

The objective of this research is to provide a better understanding as to how SAP's influence various concrete properties. This will be achieved by investigating a wide variety of bonded concrete overlay characteristics. It is hoped that the addition of SAP's will reduce crack propagation of bonded concrete overlays. Furthermore, it is hoped that the results of the extensive testing will be in agreement with current research on SAP characteristics and that the results of the testing can be used as a basis for more focussed testing into how SAP's can improve concrete overlay performance.

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1.6 Research Approach

This research will cover a systematic approach to investigate the influence of SAP's on patch repair performance. A detailed outline of the experimental approach is documented in Figure 1.2.

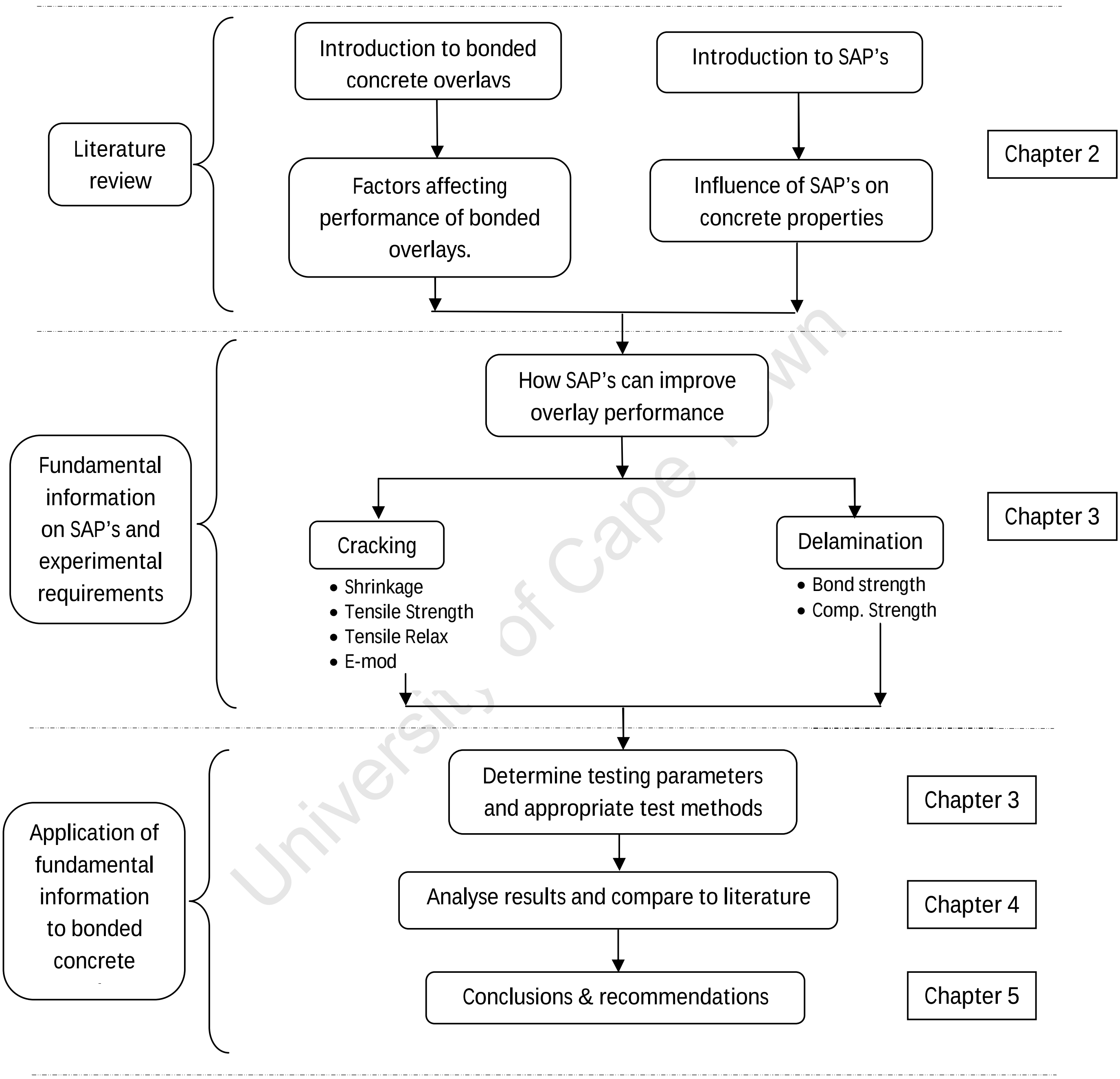

Figure 1-2: Schematic of thesis structure and methodology

Chapter 2 will serve as an introduction to the general concepts relating to bonded concrete overlays and superabsorbent polymers. It also discusses the applications of bonded concrete overlays, along with the problems associated with them. Furthermore, it also details methods to mitigate shrinkage and introduces the concept of internal curing and SAP's. Chapter 3 discusses the methodology used to investigate how SAP's can be used to improve bonded concrete overlay performance. Chapter 3 also discusses the experimental approach followed in this research. The results of the various testing conducted are shown and discussed in Chapter 4. Chapter 5 will deal with the recommendations and conclusions based on the results of this research. All references used in this thesis are shown in Chapter 6.

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2. REVIEW OF BONDED CONCRETE OVERLAY CONSTRUCTION

A bonded concrete overlay is a layer of concrete or mortar, seldom thinner than 25 mm that is placed on top of a pre-existing concrete surface. A bond develops between the new and old concrete surface. Its main use is to either restore or improve the function of the previous surface. It may also be a polymeric concrete usually less than 10 mm thick (ACI, 1999).

2.1 Applications of bonded concrete overlays

Overlays also referred to as toppings, are used for a broad range of applications including repair and surface decoration. Concrete structures deteriorate over time and may no longer meet their performance specifications. Repairing of a concrete structure by the installation of a concrete overlay is done in order to restore the structure to its original specifications. Common applications of this technique are slabs-on-grade, patch repairs, shotcrete tunnel linings, indoor and outdoor flooring (Figure 2.1) and repair of retaining walls, abutments and bridge decks (Banthia & Gupta, 2006; Beushausen, 2005). Not only is it implemented on existing structures but also on precast elements which receive an in-situ topping (Beushausen, 2005).

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Figure 2-1: Concrete floor overlay applied on existing substrate (http://www.geocheminc.com/percol11.htm)

Figure 2-2: Old concrete being removed by jack hammering to be replaced with a bonded concrete overlay (http://www.geocheminc.com/percol11.htm_)

During the service life of concrete structures, they deteriorate and often need to be repaired. The overlay technique has proved to be a reliable tool in concrete repair by providing a new surface to resist exerted loads. Allen & Edwards (1987) state that, if properly applied on concrete pavements, the overlay repair technique can achieve the following properties:

- Restoration of durability.
- Restoring structural integrity i.e. strength, abrasion resistance, etc.
- Increased structural strength of overlayed surface.
- Restoring or improving appearance of the pavement.
- Restoring the structure's fitness for use.

2.2 Factors influencing overlay performance

Overlay failure can be defined as premature cracking or debonding, which prevents the overlay from performing its required function. The occurrence of overlay failure is governed by the composition of overlay concrete, the age of the substrate concrete, the curing procedures followed, the characteristics of bond and environmental conditions such as temperature, wind and relative humidity. The composition of the overlay concrete determines material parameters such as tensile strength, elastic and visco-elastic properties and shrinkage (Beushausen, 2005). Thus, from this simple review, it is clear that with so many factors impacting bonded overlays, this is a complicated process since all factors have to be taken into account.

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2.2.1 Early-age cracking and debonding

From results of previous experimental research (Pigeon & Saucier, 1992; Kordina *et al*, 2000) as well as experience in practice, overlays have often exhibited serious performance problems when improperly applied (Beushausen, 2005). Long-term performance of bonded overlays has often been negatively influenced by early age cracking and debonding of the overlay from the substrate. Debonding is the separation between overlay and substrate characterised by overlay lifting off the substrate. If cracking and debonding are severe, premature failure of bonded overlay composite occurs. As a consequence, failure modes such as those shown in Figure 2.3 are common in bonded concrete overlays (Carlswärd, 2006).

Moisture loss from overlay may result in cracking and debonding. Firstly the overlay loses moisture to the environment due to drying. Overlays may also lose moisture to the substrate due to absorption. Depending on environmental conditions, a build-up of a humidity gradient as shown in Figure 2.3 may occur locally within the overlay. Secondly, restrained shrinkage from substrate leads to localised shear stresses at the interface. A stress field near free edges develops. The stress field tends to lift overlay edges vertically. This is shown in Figure 2.3 by curling or edge lifting. Un-controlled cracking may lead to impaired load capacity or durability, decreased stiffness and increased deformations of the structure (Carlswärd, 2006). Therefore a successful bonded overlay repair procedure has to result in very minimal or no cracking and debonding.

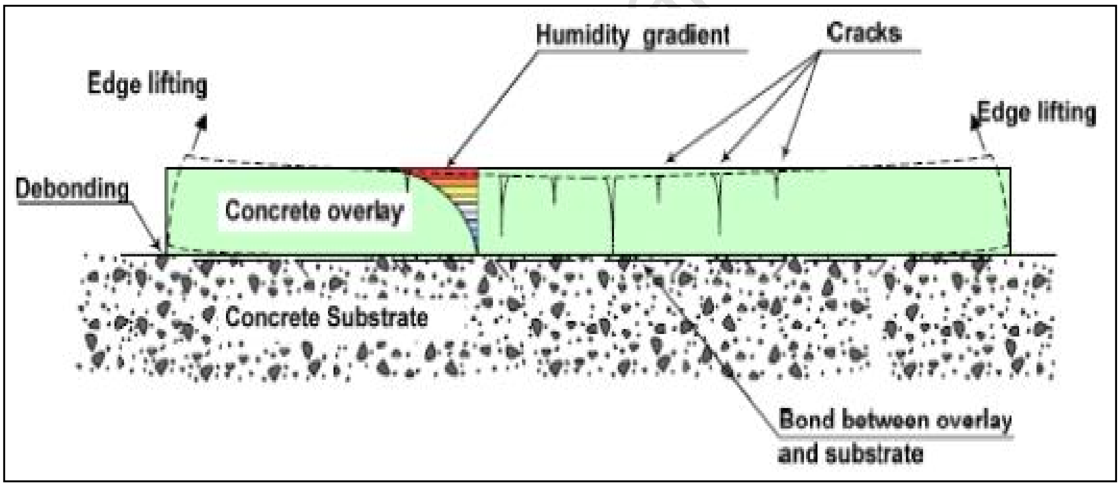

Figure 2-3 Failure modes of concrete overlays (*Carlswärd, 2006)*.

Cracking of concrete overlays commonly occurs in practice. Cracking on concrete overlays is caused by various factors such as restrained shrinkage and differing temperature gradients. These factors cause differential stresses to develop in the concrete overlay. Concrete develops its strength during the hydration process. However this process takes time and at early ages concrete is vulnerable to cracking as its tensile strength develops slowly. Cracking occurs in a concrete overlay when the stresses within the concrete overlay exceed the resistance to cracking. Once cracked, an overlay has failed as it can no longer perform its required function.

The first form of shrinkage that occurs at early ages is plastic shrinkage. Plastic shrinkage, also known as capillary shrinkage, is the result of surface moisture loss and often results in surface cracking.

Plastic shrinkage involves the transfer of moisture from the surface to the environment by evaporation or absorption of moisture by the substrate and a simultaneous mass transfer from inside the concrete to the surface. Environmental conditions such as high wind velocity, high air temperature and low relative humidity lead to an increase in plastic shrinkage (Beushausen, 2005). Suction of water by the substrate may add to the effect of surface evaporation. High early age volume changes may cause significant intrinsic stresses.

Early age shrinkage, which is commonly measured as the 0-24 hour curing shrinkage, can be of significant magnitude. According to Emmons *et al* (1995) cracks caused by plastic shrinkage occur commonly shortly after setting and can most effectively be controlled by keeping the repair surface moist during this period. Mueller *et al* (2002) claimed that plastic shrinkage can be completely eliminated through mix design and curing procedures and good site practices such as revibration.

Once the overlay has transitioned from the plastic to the solid state, drying shrinkage is a major cause of any additional cracking.

Several measures can be used to reduce the risk of cracking. The most obvious method to reduce cracking is to mitigate shrinkage, as shrinkage is the driving force in stress build up within concrete overlays. This can be achieved by optimising your concrete mix design. Shrinkage usually only occurs in the cement paste. One method to reduce shrinkage is to reduce the cement paste content by increasing the quantity of coarse aggregate in the mix.

Nmai & Balaguru (as quoted by Carlswärd, 2006) state that the effects of an increase in coarse aggregate are twofold. A high coarse aggregate quantity will reduce the water and paste demand of the mix, while also providing restraint to drying shrinkage of the paste. Both these factors help to reduce shrinkage, hence reduce cracking.

Other measures that can be used to reduce cracking would be to decrease the stiffness of a concrete overlay, which will increase the strain capacity of the overlay (Carlswärd, 2006). However, this is difficult to design as the Young's modulus more or less follows the concrete strength.

The addition of reinforcement steel reinforcing bars, steel mesh or fibres into a concrete matrix can also reduce cracking. These materials provide addition resistance to cracking by changing the stress profiles within the overlay and offer resistance to tensile strains that cause cracking. Steel fibres are typically used for the purpose of limiting crack widths even though the use of so called macro fibres made of polypropylene and other polymers have increased over the last few years (Carlswärd, 2006).

2.2.2 Restrained shrinkage

Shrinkage in concrete would not pose any detrimental effect if the material was homogenous and was allowed to deform freely. However, concrete is a heterogeneous material and in a real world scenario, concrete is usually restrained internally and externally, thus, micro and macro cracking may occur.

University of Cape Town

Restrained shrinkage in concrete can be categorized into three different scales: macroscopic, mesoscopic and microscopic (Bisschop, 2002). The macroscopic scale defines the confinement of the surrounding materials such as subgrade, formwork or adjacent structural components

The macroscopic scale of restrained shrinkage may also be referred to as external restraint. The mesoscopic scale of restraint refers to restraint brought about by the aggregate or self-restraint due to the moisture gradient within the cement-paste matrix. Mesoscopic scale is also referred to as self-restraint. The microscopic level of restraint describes the hard phases in the cement paste such as hydrated cement grains or calcium hydroxide crystals.

Even though the visible cracks in concrete are usually formed by external restraints, the microcracks brought about by meso and micro restraints can be just as detrimental to the service life as that of external restraint cracks. Microcracks impact the concrete structure by means of increasing and facilitating crack initiation and propagation under load (Bisschop, 2002)

2.2.2.1 Strain due to restrained shrinkage – Overlay Specific

When concrete is allowed to shrink freely without hindrance, deformations are observed. However when a concrete overlay is bonded to the substrate, differential shrinkage between the overlay and substrate will occur. When a constraint is applied to the concrete overlay such that it cannot shrink freely, stresses are generated.

For concrete repairs of common dimensions, i.e. thin overlays on stiff substrates, effect of bending moments initiated by differential shrinkage can usually be neglected. Conversely, in members with relatively low substrate stiffness, e.g. thick structural overlays on concrete slabs, bending moments due to differential shrinkage might cause considerable curvature, resulting in compressive strain in the overlay and hence in partial relief of tensile overlay stress (Beushausen, 2005).

2.2.3 Tensile creep and tensile stress relaxation

Tensile relaxation is the reduction in stress due to imposed strain. Tensile creep is defined as the increase in strain due to an imposed constant tensile stress. On the other hand tensile relaxation is the reduction in stress due to a constant imposed strain. Cracking of overlays can be avoided if the rate of deformation is lower than the rate of relaxation (Jensen & Hansen, 2001)

Results reported in literature (Pigeon & Bissonette, 1999, Pigeon *et al,* 2000; Beushausen, 2005; Carlswärd, 2006) suggest that tensile relaxation is a major mechanism for stress relief of concrete specimens under restrained deformation. However, tensile relaxation is a complicated mechanism to analyse as concrete behaviour in tension is poorly understood. A number of researchers including Rusch *et al* (1983), Pigeon & Bissonette (1999), Pigeon *et al* (2000), Beushausen (2005) and Carlswärd (2006) have studied concrete behaviour in tension. It was concluded that the main mechanical properties affecting performance of bonded concrete overlays are shrinkage, tensile strength, elastic modulus and tensile relaxation.

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Mechanical properties influencing the performance of bonded overlays have been mentioned briefly in the preceding paragraph. A schematic of the main factors and their interrelation is shown in Figure 2.4.

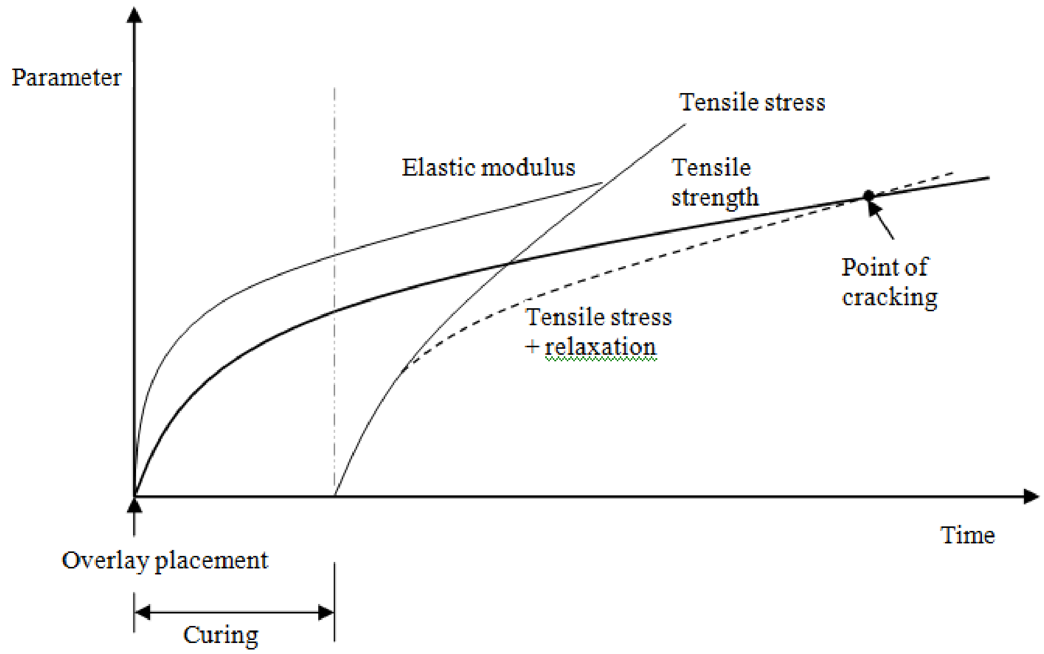

Figure 2-4: Key properties affecting performance of bonded concrete overlays (Masuku 2009).

Figure 2.4 shows the main properties affecting performance of bonded concrete overlays. After the concrete has been cast, elastic modulus and tensile strength start to increase gradually. Ignoring autogenous shrinkage, shrinkage during curing may be assumed to be very low i.e. it is considered as insignificant. As a result, once curing has been completed, drying shrinkage will start to occur. If concrete is allowed to shrink freely without restraint, no stresses develop. However, if concrete is restrained from shrinking, tensile stresses are generated in the topping. Tensile stresses increase with an increase in rate of shrinkage. Consequently, if tensile strength of concrete is less than the induced tensile stress, concrete will fail unless stresses are relaxed by tensile relaxation. Therefore tensile relaxation may delay or possibly even prevent the onset of cracking.

In tests done by Morimoto & Koyanagi (1994), tensile relaxation test specimens loaded at ages of 1 day and 3 days showed significant stress relaxation as early as 2-3 hours after loading. It was shown that tensile stress relaxation of approximately 25% and 15% was achieved for the loading age at 1 day and at 3 days respectively.

Gutsch & Rostásy, (1994) Morimoto & Koyanagi (1994) and Kordina *et al* (2000) presented findings pertaining mainly to time taken to reach ultimate tensile relaxation values. In particular, Morimoto & Koyanagi (1994) observed that ultimate relaxation decreases with the age of the concrete.

2.3 Overlay bond strength

The development of good bond strength between the old concrete substrate and the new concrete mortar is important for ensuring the durability of the repaired concrete structure. Silfwerbrand

(2003) states that a good bond allows for the repaired structure to be designed assuming monolithic behaviour. Furthermore, monolithic behaviour reduces both deflections and crack development and can thus prevent any water movement along the overlay interface (Silfwerbrand & Beushausen, 2006).

Structural reasons aside, Silfwerbrand & Beushausen (2006) state that if the bond strength requirements between the substrate and repair mortar cannot be achieved, the member size and hence the thickness of the overlay will need to be increased to meet the strength requirements. This will result in increased costs and material usage.

The performance of concrete repairs is primarily linked to their crack resistance and the strength of the bond between the old concrete substrate and the repair mortar. This is confirmed by the number of failures which are often observed in practice due to debonding and cracking due to shrinkage (Beushausen & Alexander, 2007). Beushausen *et al* note that adequate bond strength can be achieved if the quality of workmanship is good. Therefore, assuming proper site supervision and good workmanship, crack development due to shrinkage is the most critical issue for concrete repairs. The two common failure mechanisms, namely cracking and debonding, will be discussed in the following sections with special attention paid to crack development due to shrinkage.

2.3.1 Definition of bond strength and bonded concrete overlays

The literature reveals a wide interpretation of the term 'bond strength'. Beushausen & Alexander (2007) noted that bond strength is often defined as that stress which is required to separate substrate and overlay. However this could refer to both the shear stress parallel to the interface or the tensile stress perpendicular to the interface, depending on the state of stress which the structure is subjected to in the field.

Subsequently the measured bond strength of a sample is highly dependent on the test method used (Momayeza *et al*, 2005) although in most cases shear bond strength is often more interesting than tensile bond strength to designers (Silfwerbrand & Beushausen, 2006). Momayeza *et al* conclude that the measured bond strength can differ by as much as a factor of eight for different test methods which represent different states of stress.

However this contrasts with other research which has revealed a mean ratio of 1.5 (Sato, 1998) or 2.0 (Delatte *et al*, 2000) between shear bond and tension bond. It is important to note that bond strength cannot be given a universal definition. Bond strength should be defined for each situation depending on the predominant stress at the interface (Beushausen & Alexander, 2007) to avoid misinterpreting the applicable bond strength.

2.3.2 Bond strength test methods

Numerous test methods have been developed to determine the bond strength between a concrete substrate and a new concrete overlay (Figure 2.5). These tests fall into three broad categories, namely tension, shear and torsion tests (Momayeza *et al*, 2005).

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The tensile pull-off test is the most widespread test (Silfwerbrand, 2003) due to the simplicity of conducting the test either in-situ (Figure 2.5 a) or in the laboratory (Figure 2.5 b). To perform this test a core is drilled through the new and old concrete and either left attached to the structure (in-situ testing) or removed by breaking the core off the structure for laboratory testing. The tensile stress is then determined by applying a tensile force perpendicular to the concrete interface (Silfwerbrand, 2003). However, there are numerous weaknesses associated with the tensile pull-off test as test results are heavily influenced by any eccentricity in the load application or damage by coring (Beushausen & Alexander, 2007).

The consequence of any eccentricities is a large scatter of the results which can make them difficult to interpret (Momayeza *et al*, 2005). Furthermore, the tensile strength is only equivalent to the bond strength if the bond strength is less than the concrete tensile strength, allowing failure to occur through the interface (Silfwerbrand, 2003).

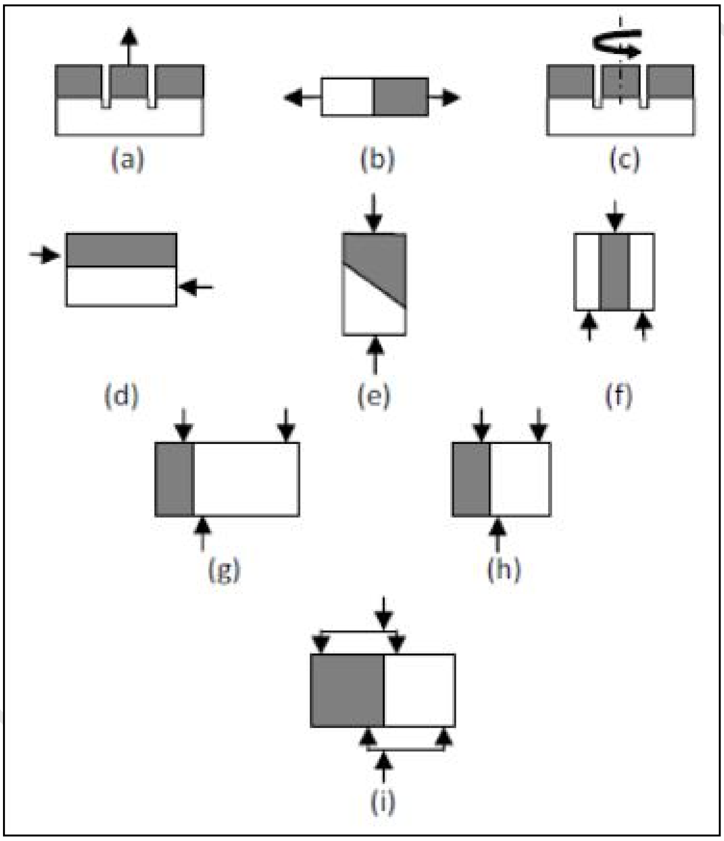

Figure 2-5: The setup of various test methods to determine the bond strength between concrete substrate and overlay (modified from Beushausen & Silfwerbrand, 2006)

The shear bond strength is more difficult to directly measure compared to the tensile bond strength and many tests make use of a combination of shear and flexure or shear and axial loads (Silfwerbrand & Beushausen, 2006). Most shear bond tests apply a force parallel to the concrete interface (Figure 2.5 d and f). The push-out test (Figure 2.5 f) experiences shear along two interfaces, which is very seldom experienced on site, making it impractical (Beushausen & Alexander, 2007). The slant shear test (Figure 2.5 e) was developed by the University of Arizona and combines the shear force with a compressive axial load (Momayeza *et al*, 2005). Shear failure in the slant shear test is directly related to the angle at which the interface is fixed. This excludes the possibility of failure at any other angle at which a more severe combination of shear and compressive forces might act. However, despite these problems, the test is still widely used by manufacturers to characterise repair products (Austin *et al*, 1999). One of the greatest problems experienced with these shear methods is that they require that the samples be prepared and tested in the laboratory (Silfwerbrand, 2003). Silfwerbrand developed an in-situ testing method in response to this problem (Figure 2.5 c). The test specimen is the same as for an in-situ pull-off test but torsional bond strength is measured and then equated to interface shear strength.

The guillotine test (Figure 2.5 g) introduces an interface bending moment due to the small eccentricities of the applied loads. Beushausen & Alexander (2007) developed a modified guillotine test (Figure 2.5 h) for testing specimens which are significantly affected by curing and environmental conditions. This was achieved by altering specimen dimensions to allow for the use of standard 150mm cubes. The force is however still applied with a small eccentricity and the stresses at the interface are calculated using stress analysis.

In order to simplify analysis of shear stresses The Federation Internationale de la Precontrainte (FIP) (as cited in Beushausen & Alexander, 2007) developed a test method that aims to induce pure shear stress along the concrete interface (Figure 2.5 i). Beushausen & Alexander developed a modified FIP test for cases where the overlay thickness is presumed to have no significant influence on the bond strength. The test still follows the principles of the FIP test but again has modified specimen dimensions to allow for sample fabrication in standard 150mm cubes.

University of Cape Town

2.3.3 Factors influencing bond strength

A large variety of factors have been identified as having at least some effect on the bond strength between an old concrete substrate and a new concrete overlay. Silfwerbrand & Beushausen (2006) attempted to rank these factors in order of importance. They identified the five most important factors as being the absence of microcracks, absence of laitance, substrate surface cleanliness, compaction of the overlay and curing. Bonding agents also influence bond strength of concrete overlays.

2.3.3.1 Compaction of the overlay

The compaction of the overlay is important in order to obtain a homogenous overlay which can help fulfil the requirement for repaired or modified structures to behave monolithically. Furthermore, effective compaction can help to eliminate the development of air pockets and ensure uniform interfacial bond (Silfwerbrand & Beushausen, 2006). Effective compaction can thus contribute to bond strength development.

2.3.3.2 Overlay compressive strength

One of the most important aspects influencing bond strength and durability is the strength of the overlay material. The importance of the strength of the overlay material can be explained by the existence of a weak transition zone between the old concrete substrate and the new concrete mortar. Bond failure between concrete repairs with well prepared substrates generally occurs in this weak transition zone with at least some failure in the substrate or overlay and seldom occurs purely at the concrete interface (Beushausen & Alexander, 2007). In their research, Beushausen *et al* note that this weak transition zone might be similar to the interfacial transition zone (ITZ) between aggregates and cement paste. However as the term ITZ refers specifically to the interface between aggregates and cement paste, they suggest that this transition zone between concrete of different ages be referred to as the 'overlay interface zone' (OIZ).

Although the overlay interface zone between concrete of different ages has not been fully investigated, it is believed that it behaves and is affected in a similar manner to the ITZ (Beushausen & Alexander, 2007). Jacques Farran, in the first detailed study on the ITZ in 1956, noted that the ITZ consisted of a different mineralogy and microstructure compared to the rest of the concrete (Gengying *et al*, 2001). van Mier (as cited in Silfwerbrand & Beushausen, 2006) states that the ITZ is a highly porous zone consisting of weak calcium hydroxide (CH) crystals, ettringite and calcium silicate hydrate (CSH). According to van Mier, the high porosity of the ITZ is as a result of the absorption of mixing water at the surface of the aggregates which leads to an increase in the w/b ratio.

However, this view has been disputed by numerous studies which suggest that this porosity is as a result of the wall effect (Ollivier *et al*, 1995; Scrivener *et al*, 2004). Scrivener *et al* state that the wall effect is based on the idea that the placement of a relatively large aggregate particle in a random arrangement of cement particles cannot be done without disrupting the random arrangement of these grains (Figure 2.6). This results in a zone close to the aggregate which contains less cement grains in the fresh state, most of which are relatively small, leading to a higher effective w/b ratio. This zone has a relatively high porosity which combined with the high w/b ratio contribute to the weakness of the ITZ. Conversely the larger grains are found further away from the interface in the bulk paste which has a relatively lower porosity and w/b ratio. Ollivier *et al* (1995) suggested that the wall effect can be minimised by the addition of silica fume as the ITZ is densified by the small silica fume particles.

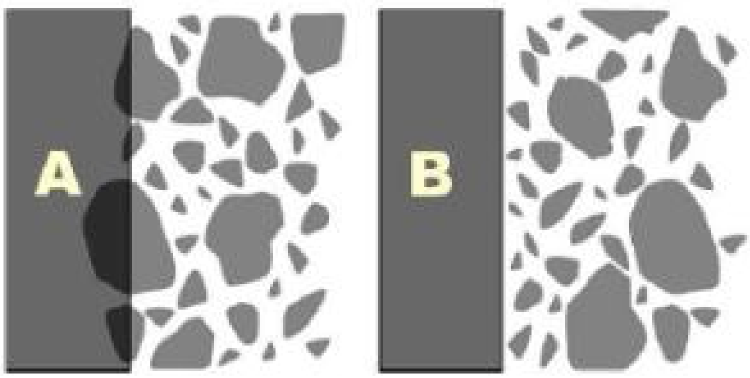

Figure 2-6: Illustration of the wall effect between aggregates and cement paste (Scrivener *et al*, 2004)

Beushausen & Alexander (2007) measured the development of interface bond strength with time and found that the compressive strength of the concrete overlay has a significant effect on the interface shear bond strength. Beushausen & Alexander further found that there is a relatively constant ratio of 0.10 – 0.12 between the interface shear bond strength and the compressive strength of the overlay for all specimens, regardless of age. As this ratio is constant it appears that it can be used as an indicator for bond strength development, assuming fully bonded conditions.

Beushausen & Alexander (2007) also found that the shear bond strength of a specimen relates to the strength of the overlay material. This was noted due observations of bond failure often occurring in the overlay near the interface. However these tests were only performed on specimens in which the overlay strength was less than the substrate strength and should an overlay of higher strength be used it is expected that the bond failure will occur in the substrate concrete. In such a case the shear bond strength will be proportional to the shear bond strength of the concrete substrate. Beushausen *et al* recommend that that designs for bond strength should not only be based on the properties of the interface, but also on the mechanical properties of the repair mortar.

2.3.3.3 Substrate surface preparation and cleanliness

Bonded concrete overlay repair involves removing the deteriorated concrete layer near the substrate surface and replacing it with a thin concrete layer (Atashi *et al*, 2007). Beushausen (2005), Carlswärd (2006) and Atashi *et al* (2007) state that, for overlays to perform effectively, concrete overlay must be fully bonded to the substrate. They agree that the substrate surface should ideally be treated by shot blasting, water-jetting or sandblasting processes. This creates a surface profile that promotes development of a strong bond between the two composites. In their research spanning over a decade, Morgan (1996), Kim & Nelson (2004) and Meftah *et al* (2006) agree that performance of bonded concrete overlay composites is dependent on quality of the interface bond. They affirm the need for the substrate surface to be clean and free from grit and dust. These elements may create locations within the interface where delamination may initiate. Emmons *et al* (1995) state that proper overlay compaction results in increased bond strength.

Delatte *et al* (1998) propose that formation of interface bond is mainly due to two components. These are interlock and adhesion. Interlock is determined by the roughness of the repaired surface. Adhesion is produced by development of chemical bonds between concrete paste and cured substrate (Atashi *et al*, 2007). Adhesion mechanisms have also been briefly discussed by Beushausen (2005) citing the work of Fiebrich (1994). Fiebrich (1994) detailed that mechanisms are divided basically into mechanical interaction, thermo-dynamic mechanisms and chemical bonding. However, intricate details relating to these individual bonding mechanisms will not be dealt with in this study. For further details, readers are referred to the literature.

Silfwerbrand & Beushausen (2006) identified surface cleanliness as the most significant factor influencing bond strength. Cleaning is usually done using a high pressure water jet and Silfwerbrand & Beushausen (2006) state that surfaces should be cleaned twice. The first cleaning should be done after concrete removal to prevent free particles from bonding to the substrate surface and the second cleaning should be done just before the repair mortar is placed.

2.3.3.4 Moisture condition of the substrate

The moisture condition of the concrete substrate should be carefully considered when placing a new concrete mortar as this could affect the water-to-binder (w/b) ratio and hence the strength of the mortar. Silfwerbrand & Beushausen (2006) state that an excessively dry substrate surface may absorb too much water from the repair mortar resulting in a weak porous zone near the repair interface. They further state that if the substrate surface contains excessive moisture, a zone with a high w/b ratio and hence reduced strength will develop near the interface. This view is confirmed by

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Austin *et al* (as cited in Julio *et al*, 2004) who state that an overly dry or wet concrete substrate surface will result in a weak bond at the repair interface.

In order to achieve an acceptable bond, it is generally recommended that the substrate should be saturated and the surface dried before the repair mortar is placed (Julio *et al*, 2004). Beushausen & Alexander (2007) state that wetting the concrete for 24 hours and then allowing the surface to dry represents a near perfect condition for the development of good bond strength. However, recent research suggests that this saturated, surface dried condition has no positive effect on the bond strength and may actually result in lower bond strengths compared to dry substrates (Letele & Beushausen, 2007).

2.3.3.5 Bonding agents

Bonding agents increase bond strength particularly in stiff repair mortars that are unable to fully interact with the substrate. Therefore they cannot undergo full interlock and adhesion. For instance, bonding agents such as Portland cement grout, latex-modified Portland cement grout and epoxy resins, are sometimes used to improve the bond (Beushausen, 2005). Careful surface preparation and use of suitable bonding agents can improve bond strength. However poor workmanship has often resulted in improper application of bonding agents, which has caused subsequent interface failure in bonded overlays (Yuan & Marosszeky, 1994).

2.3.3.6 Absence of microcracks in the substrate concrete

After removing unhealthy concrete, it is important that any remaining concrete substrate be free of microcracking. The presence of microcracking will result in a zone of weakness which could act to lower the interfacial bond strength of the repaired concrete structure. The severity of microcracking is largely dependent on the method of concrete removal. (Silfwerbrand & Beushausen, 2006)

Jack hammers are used extensively for the removal of weak and damaged concrete. However, jack hammers are known to promote substrate damage which can lead to severe microcracking (Julio *et al*, 2004). The removal of concrete by water jetting is an effective method which does not result in heavy microcracking and can provide twice the bond strength compared to jack hammering (Silfwerbrand & Beushausen, 2006). Similar favourable results were confirmed by Julio *et al* for the method of sand blasting.

Although sand blasting and water jetting have been identified as the best methods for removing unhealthy concrete, acceptable results can be achieved by jack hammering followed by sand blasting (Julio *et al*, 2004). Silfwerbrand & Beushausen (2006) also note encouraging results for the method of jack hammering followed by water jetting.

2.3.3.7 Absence of laitance

Laitance is the weak layer of fine particles which accumulate on the top surface of concrete as a result of bleeding. This layer is usually removed with the old unhealthy concrete. However in some cases the new concrete mortar is placed directly on the unchanged concrete substrate, usually to improve the strength of a structure as opposed to repairing the structure. In such a case it is

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important for this laitance to be removed as failure to do so could lower the bond strength drastically. Laitance can usually be removed by sandblasting (Silfwerbrand & Beushausen, 2006).

2.4 Deformations of Hardened and Hardening Concrete

2.4.1 Mechanisms of Shrinkage

Due to its chemical nature, concrete has been observed to undergo a significant amount of deformation during its service lifetime, especially at early ages. Most of this deformation occurs within the concrete paste due to water loss however certain aggregates have also been noted to contribute to the deformation (Lam, 2005). In concrete repairs the repair mortar commonly undergoes shrinkage, leading to crack development, while deformations in the concrete substrate are negligible (Beushausen & Alexander, 2007). As debonding begins at discontinuities, these cracks can have a significant impact on the bond strength and durability of the concrete repair (Granju *et al*, 2004). This is confirmed by Silfwerbrand & Beushausen (2006) who found in their research that overlay shrinkage can reduce the shear bond strength by as much as 25% and they suggest that the control of overlay shrinkage is vital for the durability of concrete repairs.

2.4.1.1 Plastic shrinkage

Plastic shrinkage is the volume reduction of concrete due to rapid removal of water from the concrete surface during early ages. Plastic shrinkage often results in the formation of cracks on the surface of the concrete. The principal cause of these cracks is the rapid removal of water from the concrete. In the case of concrete slabs placed in situ, water loss is mainly from the exposed surface of the concrete. When the rate of evaporation exceeds the rate of bleeding, the surface concrete loses water and decreases in volume. Tensile stresses are induced in the surface concrete because of restraint by the non-shrinking inner concrete. When these stresses exceed the tensile strength of the surface concrete, cracks develop (Kellerman & Crosswell, 2009).

The rate of evaporation of water from the concrete surface increases with:

- Higher concrete temperatures
- Higher ambient temperatures
- Lower ambient relative humidities
- Higher wind velocities

In addition, water may also be absorbed by dry subgrade or absorbent formwork in direct contact with the concrete. This may aggravate water loss and, if shrinkage is restrained by subgrade or formwork, increase the likelihood of plastic shrinkage cracking (Kellerman & Crosswell, 2009).

Plastic shrinkage cracks are typically observed in concrete elements with a high surface area to volume ratio e.g. in thin bonded overlays. These cracks are roughly straight but discontinuous and closely spaced depending on dimensions of the specimen (Kellerman & Crosswell, 2000). In overlays with large surface area, crack patterns due to plastic shrinkage are random.

Several researchers (Kellerman & Crosswell, 2009; Banthia & Gupta, 2006; Atashi *et al*, 2007) have recommended that the degree of early age shrinkage can be reduced by good curing practice. This is

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because curing prevents the surface from drying out. Consequently this reduces the effects of surface cracking.

Bissonette & Pigeon (1995), Banthia & Gupta (2006) and Carlswärd (2006) showed that the use of fibres reduces occurrence of early age shrinkage cracks. In this case, fibres bridge cracks formed and prevent them from widening. Temperature control, shielding from high winds, reduced use of admixtures that prevent bleeding and the use of shrinkage reducing admixtures are recommended in the construction of overlays (Banthia & Gupta, 2006).

2.4.1.2 Chemical Shrinkage

Chemical shrinkage is due to the chemical reactions which take place as the concrete hydrates. Tazawa (as cited in Lam, 2005) states that these reactions result in the volume of the hydration products being less than the total volume of the unhydrated cement and mixing water. Although chemical shrinkage has a significant effect on the deformation of the concrete, it has no significant detrimental effect on the microstructure or macrostructure of the concrete (Lam, 2005). Lam states that this is due to the fact that most of the chemical shrinkage takes place when the concrete is in a plastic state. However other research has found that most of this chemical shrinkage is translated into internal voids within the hardened cement paste (Tazawa, 1999).

2.4.1.3 Autogenous shrinkage

Autogenous shrinkage occurs as a result of the self-desiccation or internal drying of the concrete which is in turn a result of the continuing hydration process of the cement (Kovler & Jensen, 2006). This continuing hydration absorbs water from the fine pores within the set microstructure and results in the formation of water menisci which induces compressive stresses (Figure 2.7) within the microstructure (Geiker *et al*, 2004). Geiker *et al* state that the magnitude of this compressive stress is influenced by the "meniscus radius of the largest water-filled pore within the microstructure".

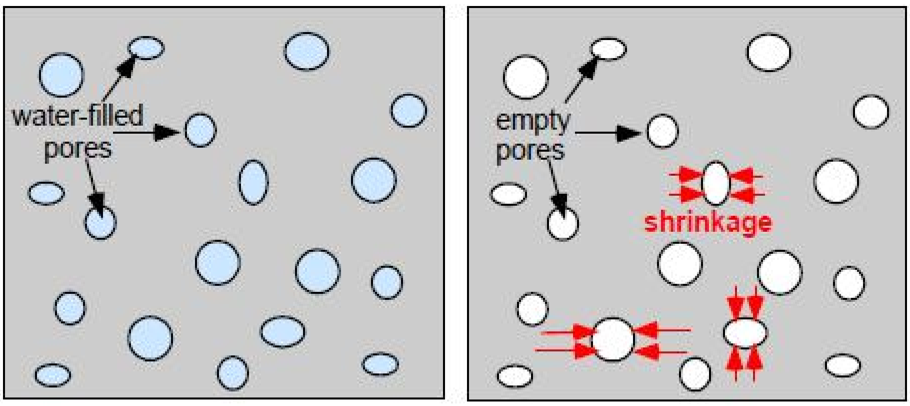

Figure 2-7: Self-desiccation of pores results in compressive forces in concrete microstructure (Hood, 2009)

Kovler & Jensen (2006) state that autogenous shrinkage is driven by chemical shrinkage and that the two are roughly equal when the concrete is in a fluid state. They further state that the chemical shrinkage becomes more significant after the setting time once the concrete is self supportive. Conversely, Tazawa (as cited in Lam, 2005) notes that the autogenous shrinkage only begins once the concrete reaches its setting point and has developed a self supportive skeleton.

According to Kovler & Jensen (2006), autogenous shrinkage is especially critical in high performance concretes which typically have a low w/b ratio. This view is confirmed by the works of other authors who suggest that concretes with a low w/b ratio experience significant self- desiccation and hence autogenous shrinkage (Persson, 1997). According to Lam (2005) this self-desiccation is due to the finer porosity in concretes with a low w/b ratio. This fine porosity and low relative humidity (RH) results in a greater radius of curvature of the water meniscus causing large compressive stresses on the pore walls. These stresses pull the paste inwards and result in a greater autogenous shrinkage. However, Lura *et al* (2003) state that although there is an agreement that there exists a relationship between autogenous shrinkage and the relative humidity of the pores in the cement paste, the actual mechanisms are unknown.

2.4.1.4 Carbonation shrinkage

Carbonation shrinkage is the decrease in concrete volume due to the reaction of hardened cement paste constituents in concrete with atmospheric carbon dioxide. Consequently carbonation may result in lower strength, increase in deflection and cracking (Matsushitaa *et al*, 2004). Carbonation shrinkage takes a long time to occur. Hence laboratory tests for carbonation shrinkage are often accelerated by forcing high concentrations of carbon dioxide through concrete specimens in order to obtain results.

Carbonation is mainly a function of relative humidity and concrete permeability. At intermediate relative humidities between about 50% and 80%, maximum carbonation shrinkage occurs (Sauman, 1971). At a relative humidity greater than 80%, carbon dioxide cannot penetrate the water-filled pore spaces easily and at lower relative humidities, below 40%, the absence of water films reduces the extent of carbonation (Alexander & Beushausen, 2009).

2.4.1.5 Drying shrinkage

Drying shrinkage is caused by loss of moisture from concrete to the environment. Evaporation of free water from capillary pores results in a decrease in the volume of concrete. Development of drying shrinkage is initially rapid and slows down as the material ages. This is due to the slow rate at which moisture is lost from concrete. Hence the strain response is time dependent. According to Asad *et al* (1997), drying shrinkage of cementitious materials is caused principally by contraction of calcium silicate hydrate (C-S-H) gel in hardened cement paste.

Cement based materials generally dry non-uniformly due to their location relative to the external environment and dense pore system; as a result, a moisture gradient can arise across the material. This differential in moisture gradient across the material gives rise to the phenomenon of what is termed curling and warping (Lam, 2005). Figure 2.8 illustrates the stresses that arise due to differential shrinkage.

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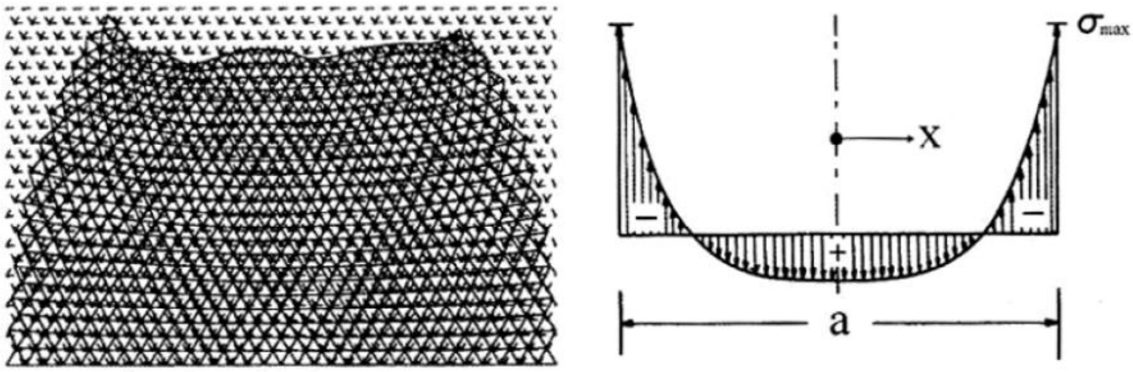

Figure 2-8: Model of stresses that arise due to differential drying shrinkage (Bisschop, 2002).

2.4.2 Fundamental mechanisms of drying shrinkage in concrete

A number of mechanisms contributing to drying shrinkage of concrete have been detailed in literature (Alexander & Beushausen, 2009; Carlswärd, 2006). The most important factor influencing drying shrinkage is the amount and composition of cement paste. It is within the cement paste that water is lost and volume changes occur. Other factors influencing drying shrinkage are structural geometry and drying conditions (Carlswärd, 2006).

The paste is affected by the w/b ratio. For concrete with w/b ratios between 0.35 and 0.50 it was shown that the extent of shrinkage is directly proportional to the proportion of cement paste. In practice, this implies that for a given w/b ratio, shrinkage can be mitigated by reducing the amount of water and increasing the content of aggregates (Carlswärd, 2006).

Shrinkage is controlled by different ways in which water moves within the cement paste as well as its interaction with the environment (Alexander & Beushausen, 2009). Listed below are a number of mechanisms describing the movement of water within the cement paste and their effects on shrinkage. It should be noted that these mechanisms occur at microscale. As such, it is difficult to verify these mechanisms through conventional methods. Special methods such as spectrometry have been used (Alexander & Beushausen, 2009).

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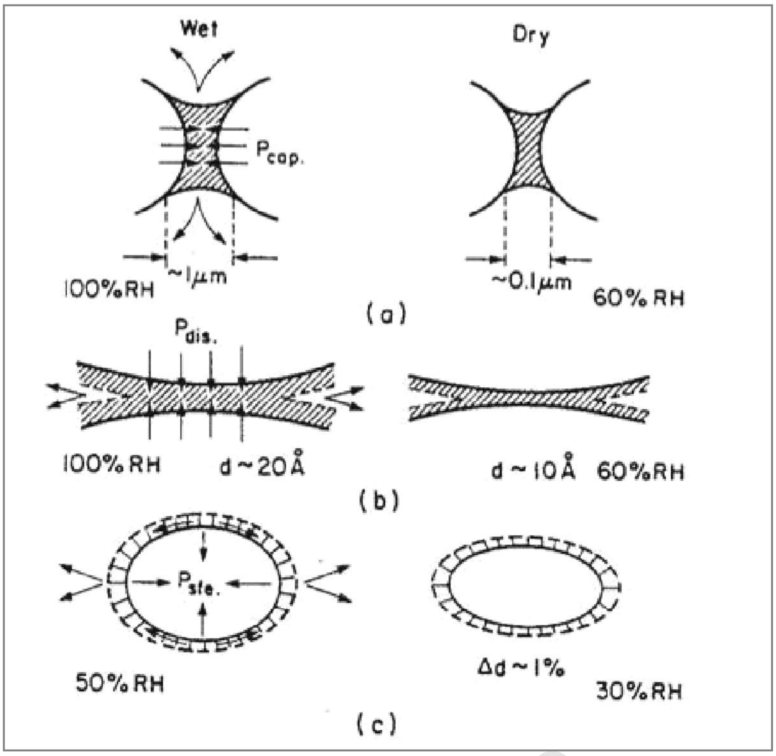

Figure 2-9: Proposed mechanisms for causes of drying shrinkage of cement paste (a) Capillary tension; (b) disjoining pressure; (c) surface tension *(Lecture Notes CIV5002Z, 2009).*

Capillary tension

In capillary tension, water is lost from the paste due to drying. This loss of water occurs in capillary pores of the paste. On drying, menisci are formed. This results in a tensile stress build-up in the capillary water (Figure 2.9 a). Tensile stresses generated must be balanced by compressive stresses in the surrounding gel causing a volume reduction (Alexander & Beushausen, 2009).

Swelling (disjoining) Pressure

As shown in Figure 2.9 (b), whenever gel particles closely approach one another, adsorbed interlayer water may exert a swelling or disjoining pressure if the free film thickness is greater than interlayer distance. In addition, drying decreases adsorbed film thickness and reduces this pressure causing shrinkage.

Surface tension

Compressive stresses occur inside solid particles due to surface tension. Drying causes surface tension to increase. This results in a corresponding increase in compressive stress in the solids, hence shrinkage (Figure 2.9 c).

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2.5 Creep & Relaxation - General

Most studies on tensile relaxation have generally used creep properties for determination of relaxation in composite systems. This may be due to lack of sufficient data accumulated on stress relaxation and in particular tensile stress relaxation (Morimoto & Koyanagi, 1994). It has been stated by Bissonnette & Pigeon (1995) that tensile properties of concrete are generally disregarded in the design of new concrete structures. As a result, difficulties related to accurate measurement of concrete tensile properties probably explain why little attention has been given to tensile stress relaxation.

When subjected to constant tensile or compressive load, for a period of time, concrete will naturally deform in the direction of the load. The resulting strain increases with time. However the increase decays gradually as the loading period is prolonged. Whenever a specimen is loaded in tension, this is called tensile creep. If it is loaded in compression, it is termed compressive creep or more commonly, creep. This is shown diagrammatically in Figure 2.10 (a) & (b).

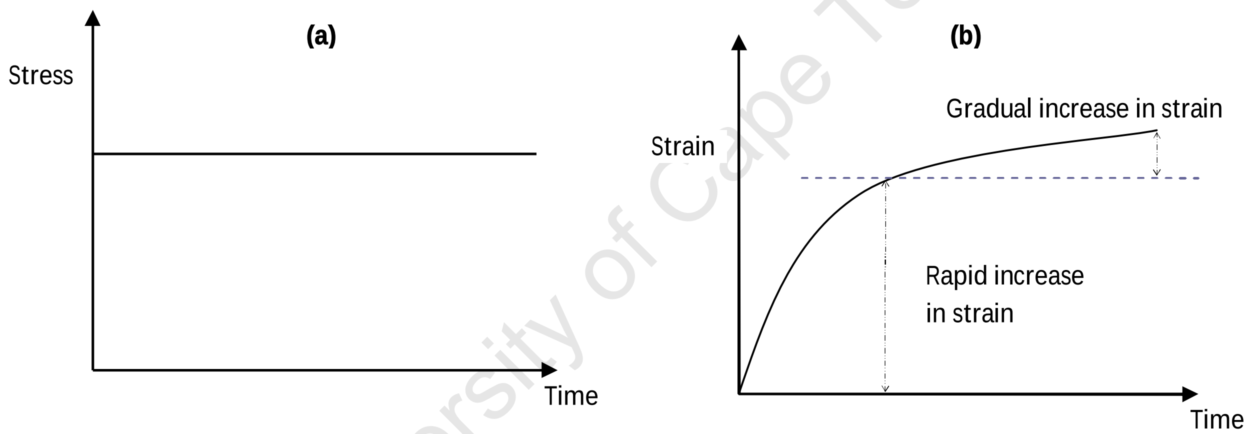

Figure 2-10: (a) Stress-time curve **(b)** Strain-time curve as a result of creep (Masuku, 2009)

When a concrete specimen is subjected to a sustained strain it undergoes relaxation. Relaxation is the general decrease in stress on a body when subjected to sustained strain. Therefore, stresses due to sustained strain are generated within the member but they decrease gradually with time. Through this research, the stress curve shall be assessed for different concrete mixes. Whenever a specimen is loaded at constant strain in tension, stress decay is termed tensile relaxation. This phenomenon is shown diagrammatically in Figure 2.11 (a) & (b).

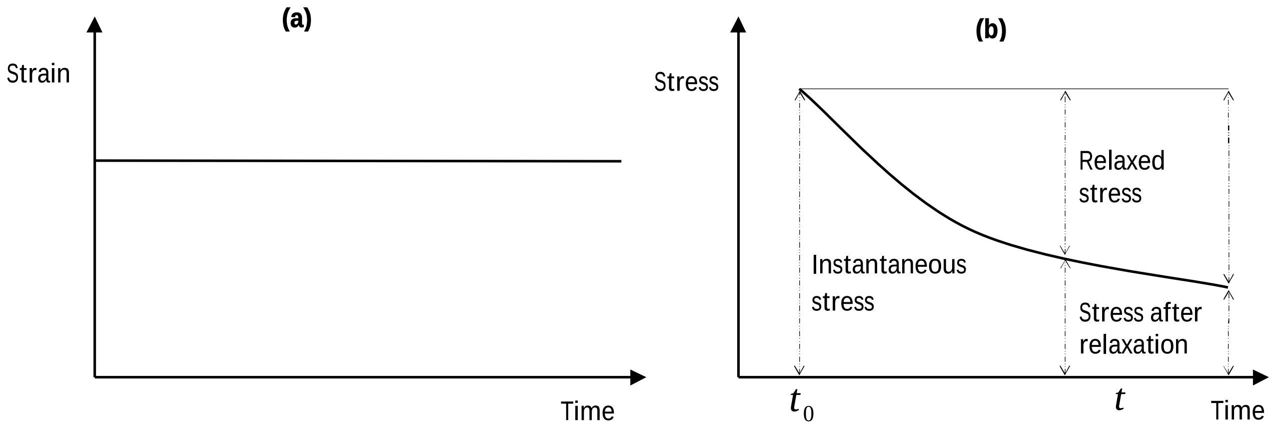

Figure 2-11: (a) Strain-time curve **(b)** Stress-time curve as a result of relaxation (Masuku, 2009)

As perceived by Morimoto & Koyanagi (1994), it seems more appropriate to use the relaxation function to express stress relaxation rather than using creep function.

2.5.1 Mechanisms of creep and relaxation

Contrary to creep in compression, which has been subject to large number of studies, little is known of the viscoelastic behaviour of concrete in tension (Pigeon & Bissonnette, 1999). On the other hand, the subject of concrete in tension has been viewed as rather less important when compared to creep in compression. This is owing to the fact that concrete is mainly used structurally in compression. This has often led to a general treatment of tensile relaxation as a similar process to creep in compression. This section attempts to outline various mechanisms involved in creep as well as relaxation of concrete.

Various authors attribute creep and relaxation to different processes. Powers (1968) explains that when concrete is subjected to sustained loading, load bearing water within cement paste moves through diffusion mechanisms. On the other hand Feldman & Sereda (1968) (as cited by Wittmann, 1981) used a different approach to investigate mechanisms involved during creep. They proposed a structure of cement paste shown in Figure 2.12 Their conclusions were that creep is caused by movement of water i.e. interlayer water between gel layers. Furthermore, movement of water causes gel layers to slide over each other causing microstructural changes. With cement paste consisting of numerous such layers sliding over each other, global deformation is imminent.

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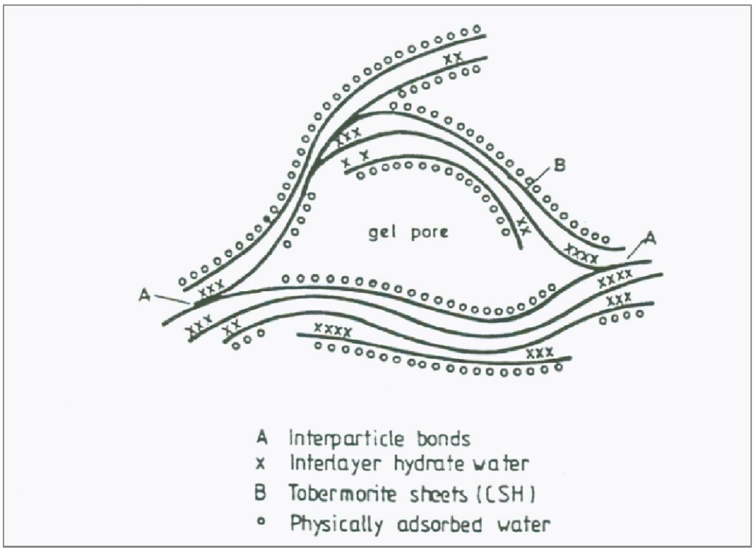

Figure 2-12: Schematic of cement paste microstructure *(Feldman and Sereda, 1968)*.

When external loads are sustained, changes may occur in the gel structure. Such changes may be reduction in interparticle spacings, reduction of layer thicknesses and displacement of gel layers. This results in formation of new bonds. The external loads mentioned in this case refer to compressive stresses not exceeding 40% of ultimate strength of concrete under consideration. At stresses higher than 40% of ultimate strength of concrete, microcracking occurs. This causes strains much larger than those induced by movement of moisture.

Some changes in the gel structure are reversible whilst others are permanent. Reversible changes constitute elastic strains or delayed elastic strains whilst permanent strain represents creep.

When subjected to tensile stresses, the behaviour of concrete is different because concrete has low tensile strength. A small number of authors attribute this behaviour to microcracking within the concrete matrix. A specific example is the work of Cook (1972) on the theory of microcracking. Moreover results obtained by Pigeon & Bissonnette (1999) indicate that sustained tensile stresses are more likely to cause the formation and opening of microcracks. This is more likely to occur at interfacial transition zones perpendicular to the loading axis. In addition, Pigeon & Bissonnette (1999) use the viscous shear theory to explain mechanisms occurring in concrete under tensile loading. In this particular study, references to the work of Brooks & Neville (1997) are made.

Gutsch & Rostásy (1994) analysed stress-strain relationship of concrete undergoing tensile relaxation. They observed that microcracking within the cement paste caused a loss of stiffness in concrete. Microcracking was detected at stresses above 730% of tensile strength in the member.

Pigeon & Bissonnette (1999) concluded that the dominant mechanism in relaxation was viscous shear and also the presence of microcracking. This was because their samples showed a small loss of rigidity. Even though there is evidence to show that the dominant mechanism is viscous shear, contribution of other relaxation mechanisms such as microcracking could not be ruled out completely.

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2.6 Mitigation of Shrinkage

The quantity of shrinkage that occurs is governed by the quantity of water present within the concrete. The simplest way to reduce shrinkage is to decrease the w/b ratio of your concrete, thus reducing the quantity of water in your mix. Hence, concrete with a lower w/b ratio undergoes less shrinkage. Lam (2005) suggests that another method to minimise shrinkage is to modify the composition of the concrete mix. As shrinkage occurs in the cement paste, increasing the amount of aggregates or conversely decreasing the amount of cement paste will decrease the shrinkage. This can be done is by increasing the percentage of aggregate in the concrete mix. However, Lam notes that these methods are not practical in situations where specific concrete properties need to be attained.

Chemical admixtures which have the ability to reduce shrinkage include shrinkage reducing admixtures (SRA) which aim to minimise the shrinkage and shrinkage compensating admixtures (SCA) which undergo expansion at early ages to offset the effects of shrinkage. Even though shrinkage reducing and shrinkage compensating admixtures have shown promising results (Lam, 2005), this research will not include any further work on this topic.

All shrinkage mechanisms described above relate to moisture loss in some form. As mentioned, this can result in the cracking of the repair mortar which in turn may initiate debonding due to the existence of free edges. According to Silfwerbrand & Beushausen (2006), curing is therefore an important factor in reducing early age shrinkage and they state that by preventing moisture loss and hence early age shrinkage the concrete will have a higher tensile strength at the eventual onset of shrinkage which will reduce crack formation.

2.6.1 Curing of Concrete

Curing is described as the maintenance of appropriate moisture and temperature conditions to permit the continuation of the hydration or pozzolanic reaction (Grieve, 2009). Adequate curing is an important property that greatly influences concrete quality. Curing has a strong influence on the properties of hardened concrete such as durability, strength, abrasion resistance, volume stability, and resistance to freezing and thawing and deicer salts (Kolver & Jensen, 2007). Insufficient or inadequate curing can significantly reduce surface strength development and impermeability.

Curing has a large impact on the hydration process. Most freshly mixed concrete contains more water than is required for complete hydration of the cement. However, any substantial loss of water by evaporation or otherwise will delay or limit hydration. If temperatures are favourable, hydration is relatively rapid within the first few days after concrete is placed. It is extremely important that as much water as possible is retained during this period. Good curing means evaporation should be prevented or reduced, which can greatly reduce shrinkage (Kolver & Jenson, 2007).

An overview of various available curing procedures can be seen below in Figure 2.13.

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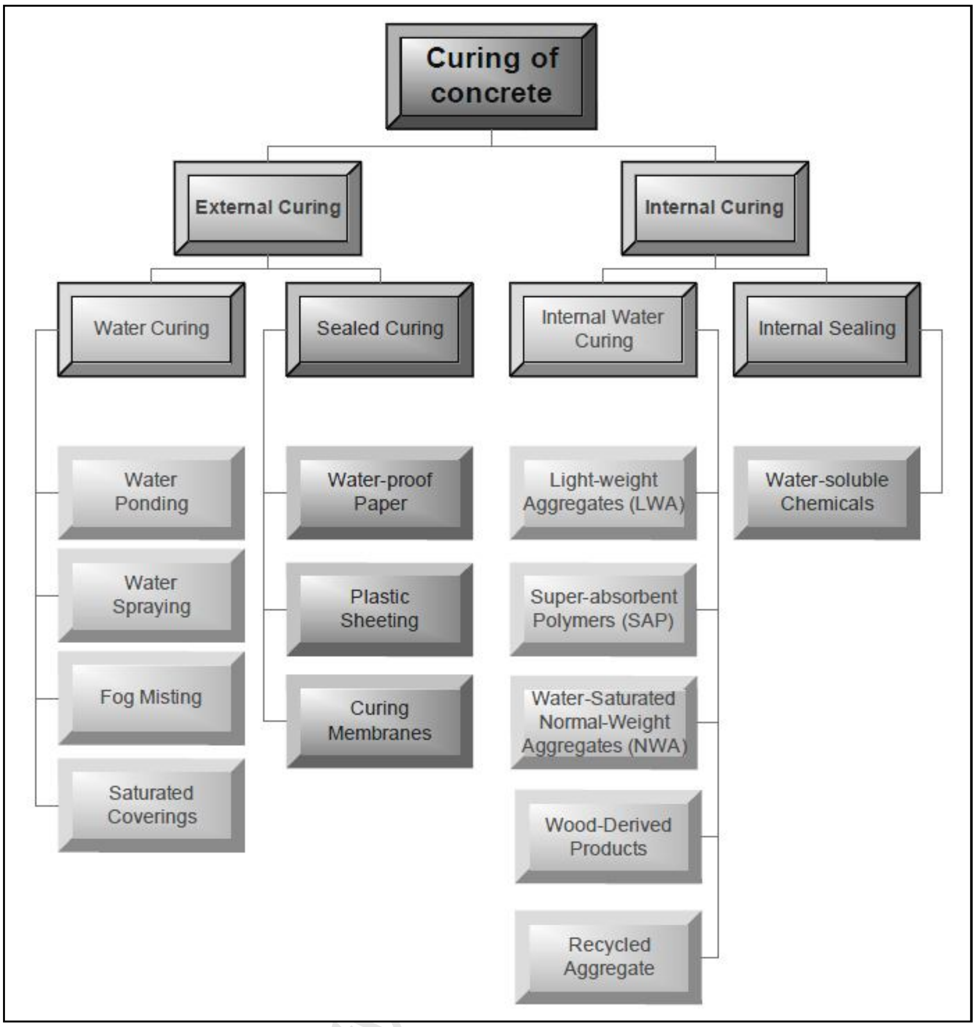

Figure 2-13: Breakdown of the available curing techniques (Kolver & Jensen, 2007)

Most of the traditional curing methods are based on externally applied curing. They are used for ordinary as well as high-strength or high-performance concrete. These methods include water ponding, water spraying (Figure 2.14), wet burlap, plastic sheeting (Figure 2.15), curing compounds and many others. In addition, various accelerated curing techniques can be applied (Kolver & Jensen, 2007).

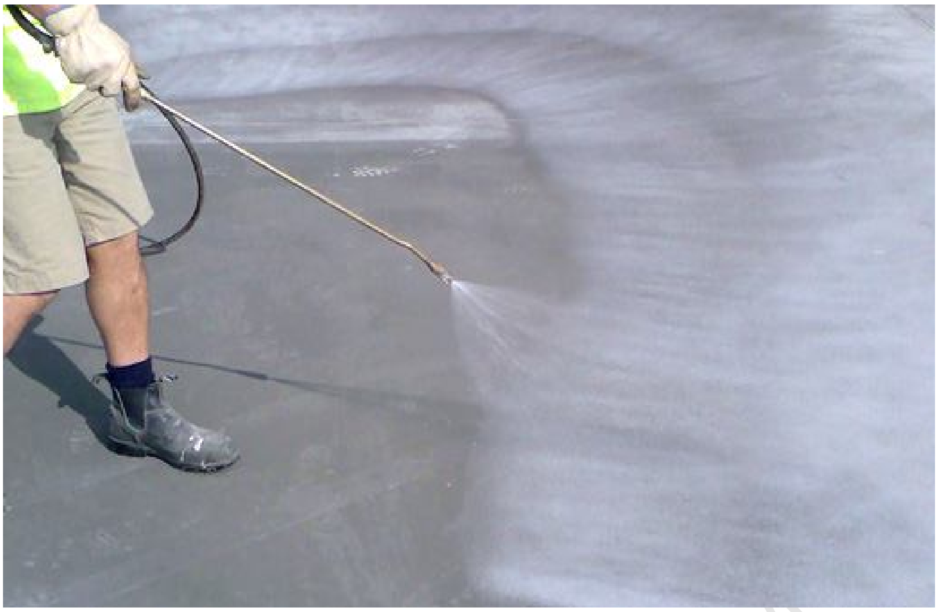

Figure 2-14: Water spraying as a method of external curing (http://www.electriccuringblanket.com/node/1)

Figure 2-15: Plastic sheeting used as a method of external curing (http://www.cuttingin.com.au/Concrete-Curing.htm)

In practice, curing has been almost exclusively carried out through external curing methods, which aim to supply water from an external source or to seal the concrete surface which will provide a restraint to moisture loss (Cusson & Hoogeveen, 2008). However Schrader (as cited in Silfwerbrand & Beushausen, 2006) states that while external curing methods influence the surface of the concrete, they have a negligible influence on material and bond properties at depths exceeding 25mm. This is especially true for high performance concrete in which the w/b ratio is characteristically low as this leads to a dense cement paste and discontinuous pore structure, which makes moisture penetration difficult (Lam, 2005). Furthermore, Zhutovsky *et al* (2004) state that self-desiccation cannot be eliminated by external curing methods.

2.7 Internal Curing

Recent research has focused on internal curing as a method of minimising moisture loss and reducing the potential for crack development. Internal curing is based on the idea of including an internal water source in the form of a water saturated material into the concrete mix (Lam, 2005). As the hydration of the cement proceeds, leading to self-desiccation, the drying cement pores create a driving force, which transports water from the internal water source to the cement matrix (Bentur *et al*, 2001). Lam states that, in theory, the internal water source maintains a relative humidity (RH) within the concrete of close to 100% and in so doing can reduce both drying and autogenous shrinkage. This is confirmed by Neville & Aitcin (1998), who state that with really good internal curing, it is possible to almost completely eliminate autogenous and drying shrinkage. Conversely, Jensen & Hansen (2001) note that ultimately the RH of the concrete has to move toward equilibrium with its external environment and this drop in RH could lead to drying shrinkage. However they note that this drying shrinkage will not take place at early ages and thus the risk of cracking is drastically reduced as the concrete strain capacity is no longer at a minimum. Neville & Aitcin further note that internal curing is especially beneficial in high performance concretes where autogenous shrinkage is dominant. Some common internal curing methods are discussed below.

2.7.1 Light-weight Aggregates (LWA)

Internal curing through the use of lightweight aggregates involves substituting a portion of the normal aggregate within a concrete mix with saturated lightweight aggregates. Lightweight aggregates typically have a vast network of internal voids or capillaries which allows for them to absorb and store water (Lam, 2005). Pumice is an example of a LWA is shown in Figure 2.16. As the concrete begins to dry internally, capillary suction forces the entrained water from the relatively large pores of the aggregate to the small pores of the cement paste (Bentur *et al*, 2001), thus helping to mitigate the effects of self-desiccation.

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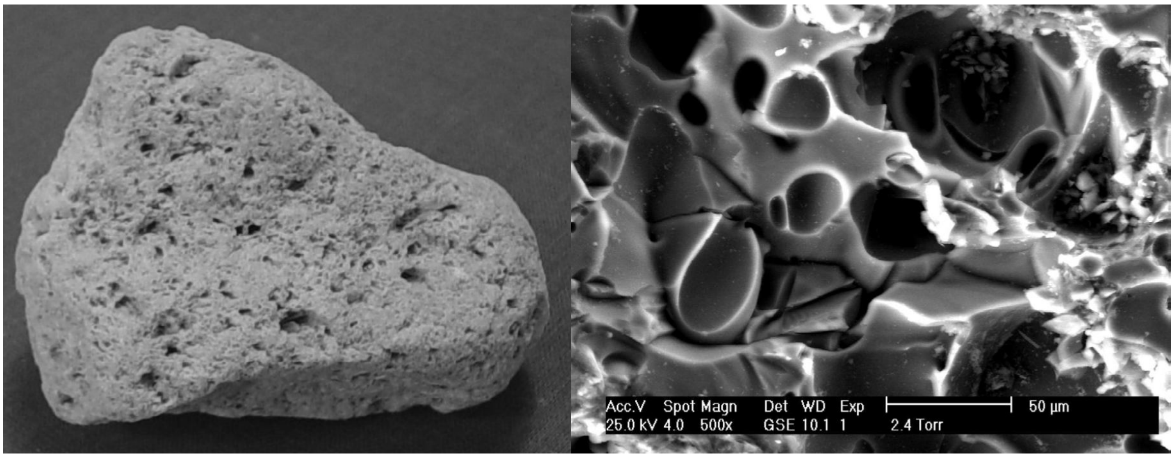

Figure 2-16: Left: 5 cm-size pumice stone particle. Smaller particles provide a more efficient water curing. A wide range of pore sizes are seen. Right: Scanning electron micrograph of a fracture surface of a pumice aggregate particle with an open porosity of 40% (Jenson & Lura, 2007).

The amount of water provided for internal curing significantly affects the success of internal curing. Bentz & Snyder (1999) developed equations to determine the amount of internal water needed to ensure complete curing of concrete and hence reduce the shrinkage. They based these equations on the amount of water lost due to chemical shrinkage as this water loss results in self-desiccation and ultimately autogenous shrinkage. Zhutovsky *et al* (2002) modified the work of Bentz & Snyder (1999) to provide Equation 1 for determining the internal water requirement.

$$w_{ic} = c \times \alpha_{max} \times cs \qquad (1)$$

Where:

w_{ic}	=	internal curing water (kg water/ m^3 concrete)
C	=	cement content (kg cement/ m^3 concrete)
α_{max}	=	maximum degree of hydration, can be estimated as (w/b)/0.40
CS	=	chemical shrinkage (kg water/kg cement hydrated)

Equation 1 usually provides values of between 18 and 23 kg/m^3, however in practice the required water quantities have generally been found to be 30 to 40 kg more than this (Zhutovsky *et al*, 2002). Zhutovsky *et al* noted that this is due to inefficiencies with regards to the ability of the water to migrate into the surrounding paste. They proposed Equation 2, which takes an efficiency factor into account, to calculate the content of aggregate required for internal curing.

$$LWA = \frac{w_{ic}}{\emptyset \times s \times \eta} \qquad (2)$$

Where:

LWA	=	quantity of lightweight aggregate (kg aggregate/ m^3 concrete)
W_{ic}	=	internal curing water (kg water/ m^3 concrete)
ϕ	=	aggregate water absorption by weight (kg water/kg dry aggregate)

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S = degree of saturation of the aggregate
η = efficiency factor i.e. the amount of absorbed water which can be effectively released

However the efficiency factor is the result of a complex function and is based on aggregate properties, cement paste properties and the spacing and dispersion of the aggregate particles (Zhutovsky *et al*, 2002). These equations are therefore impractical unless they are preceded by extensive laboratory experiments. Kovler & Jensen (2006) proposed a simple graph (Figure 2.17) to determine the minimum amount of internal curing water required in relation to the w/b ratio.

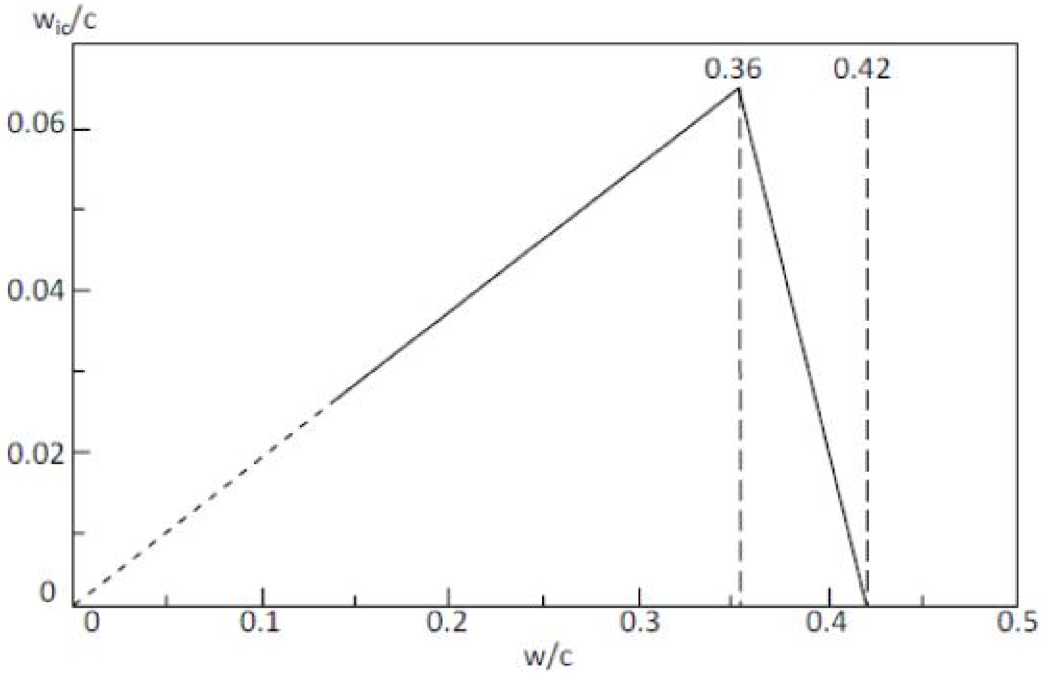

Figure 2-17: The minimum amount of internal curing water which is required to prevent the self-desiccation of the concrete during hydration expressed in terms of the internal water to cement ratio (w/b) vs. the water to cement (w/b) ratio of the concrete mix (Kovler & Jensen, 2006)

Kovler & Jensen (2006) based their graph (Figure 2.17) on Power's model, which requires that the volume of internal curing water, w_{ic}, should be equal to the amount required to obtain the maximum degree of hydration. Figure 2.17 provides a good estimation on the minimum amount of water which should be made available for internal curing. However, it does not take into account the efficiency of the aggregate. Kohno *et al* (1999) found that autogenous shrinkage decreases with an increase in the amount of water provided for internal curing. However, providing more water than the minimum amount should be done with care (Lam, 2005). According to Lam additional water may allow for additional curing of the cement paste. However, excess water may prevent the cement paste from fully bonding with the aggregate surface. The resulting ITZ could form with a high porosity, which could then impact on the performance and durability of the concrete. Kovler & Jensen state that for w/b ratios below 0.36, even with internal curing, complete hydration is not possible as the hydration process will be limited by the available space for reaction products. Bentz & Snyder (1999) confirm this idea but state that complete hydration is not possible for w/b ratios of 0.40 and below.

Various works have shown that the use of LWA's is an effective means of minimising shrinkage, especially autogenous shrinkage (Geiker *et al*, 2004; Bentz & Stutzman, 2006; Cusson & Hoogeveen, 2008). Zhutovsky *et al* (2002) state that by controlling the size and porosity of the LWA, it is possible to virtually eliminate all autogenous shrinkage without any external curing. According to Cusson *et al*, the saturated LWA's allow for the early age expansion of the concrete which offsets the adverse effects of shrinkage. The LWA's also decrease the possibility of thermal shrinkage by decreasing the heat of hydration (Lam, 2005). Furthermore Lam states that the LWA can absorb excess bleed water, helping to decrease the porosity and hence to increase the strength of the ITZ.

According to Lam (2005), the main drawback of the use of LWA's for internal curing is their adverse effect on the compressive strength of the concrete. Lam states that this is due to the LWA generally being weaker than normal weight aggregates. However this view is contradicted by various works which show that the use of LWA's can increase the long term compressive strength of the internally cured concrete (Geiker *et al*, 2004; Lura *et al*, 2004; Bentz & Stutzman, 2006; Cusson & Hoogeveen, 2008). According to Bentz & Stutzman, this increase in strength is due to the increased hydration of the cement.

2.7.2 Internal Sealing

Internal sealing of concrete refers to techniques where the water loss from the concrete is mitigated by the addition of a special curing agent. Dhir *et al* (1994) have suggested that mechanisms active in internal sealing may include lowering of the chemical potential of the pore water or blocking of the surface pores.

Melbye (1998) has also suggested an innovative technique for internal sealing. By adding a paraffin emulsion to the concrete mixture, enhanced water proofing of the concrete was achieved, and by adding a polyethylene oxide, the water retention of the concrete was improved. A combination of these two techniques is suggested to be especially useful to prevent plastic shrinkage during shotcreting.

2.7.3 Superabsorbent Polymers (SAP's)

SAPs are a group of polymeric materials that have the ability to absorb a significant amount of liquid from the surroundings and to retain the liquid within their structure without dissolving. SAP's are readily available with approximately 500 000 tons of SAP produced annually. They are currently found in high-tech materials such as contact lenses, breast implants, fire fighting, drug delivery, in baby diapers and as soil conditioners (Jensen & Lura, 2007). They can also be used as a method internal curing in concrete.

Some SAP's have the potential to absorb up to 5000 times their own weight. However, in dilute salt solutions such as urine, the absorbency of commercially produced SAPs is around 50 g/g (Jenson & Hanson, 2001). Figure 2.18 shows two different SAP particles in both the dry and hydrated state. The smaller particle in each photo is the unhydrated, dry SAP particle and the larger particle has absorbed some water into its microstructure.

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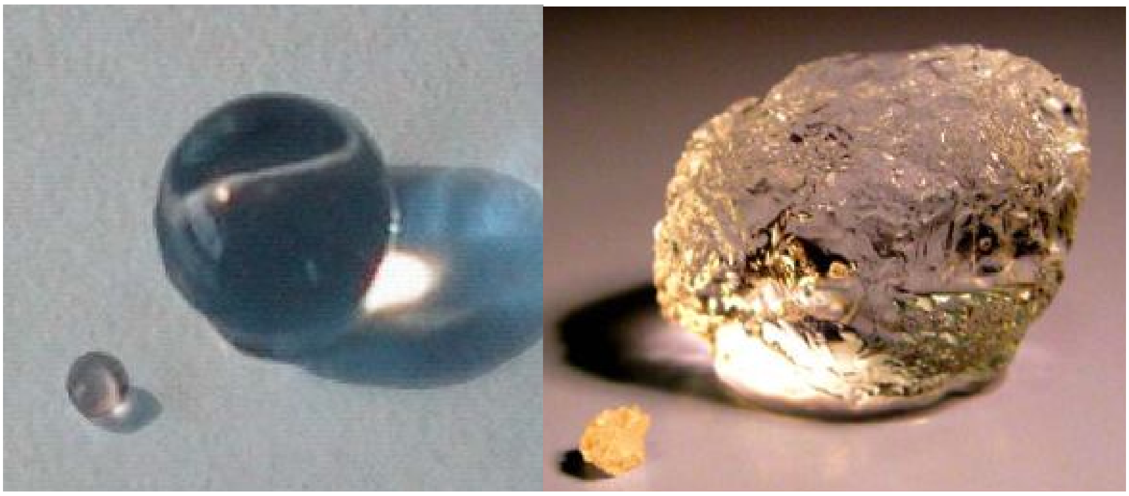

Figure 2-18: Examples of collapsed, unhydrated SAP particles and swollen SAP particles (Jenson & Hanson, 2006; Lautsen *et al*. 2008).

Many different types of SAPs are known. They can be produced by either solution or suspension polymerization, and the particles may be prepared in a variety of different sizes and shapes including spherical particles. The commercially important SAPs are covalently cross-linked polyacrylates and copolymerized polyacrylamides/polyacrylates. An example of the long chains within the SAP structure can be seen in Figure 2.19. Because of their ionic nature and interconnected structure, they can absorb large quantities of water without dissolving. From a chemical point of view, all the water inside a SAP can, essentially, be considered as bulk water (Jenson & Hanson, 2001).

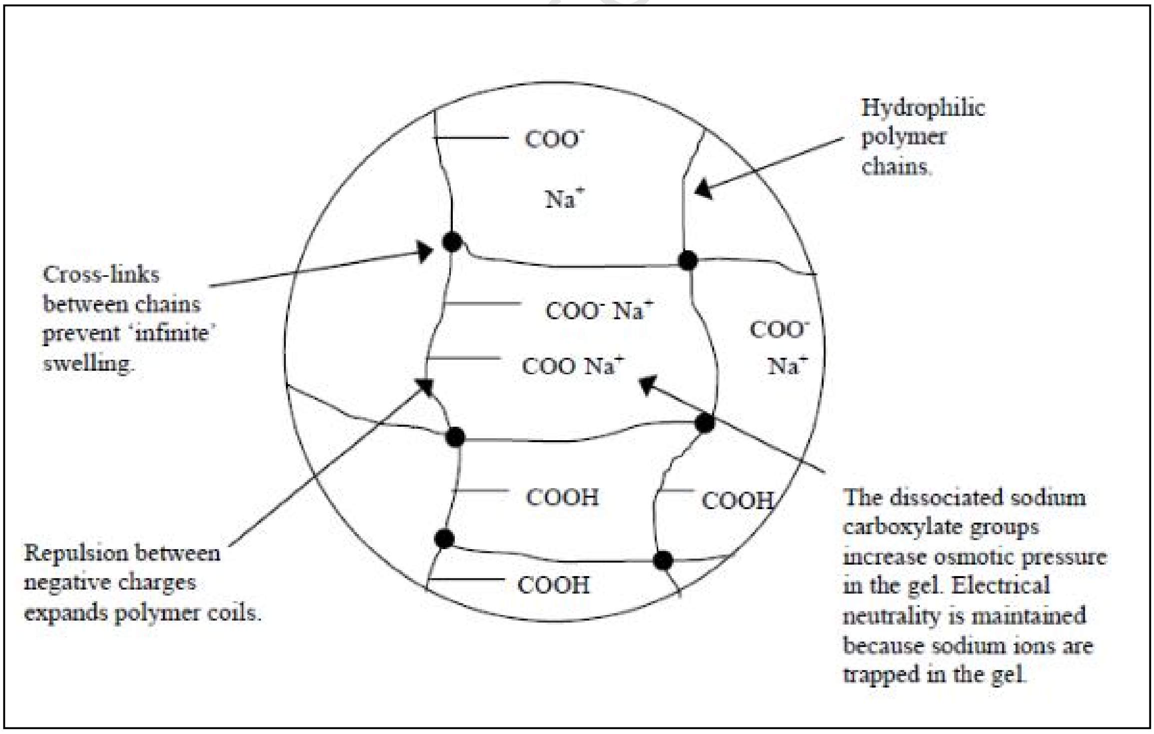

Figure 2-19: Diagrammatic representation of part of the SAP network (M. Elliot, 2004).

According to Lam (2005), when the saturated SAP's are incorporated into the concrete mix, they release their stored water due to the ionic properties of the cement paste and the continuing hydration. Theoretically this water would then be available within the concrete to offset the effects of self-desiccation. However it is further noted that as internal curing by SAP's relies on chemical reactions, mix designs need to be thoroughly tested as different cementitious materials and chemical admixtures can adversely affect these reactions.

SAP's can either be saturated before they are mixed into the concrete or while they are mixed with the concrete. If the SAP's are saturated before they are added to the concrete mix, it is important that they be durable enough to withstand the mixing process without losing their stored water (Jensen & Lura, 2006). During his research, Lam (2005) noted that concrete in which the SAP's were added in a saturated state displayed excessive bleeding. This contributed to water being prematurely forced out of the SAP particles due to deformations induced by the mixing process. Due to their ionic nature, the SAP particles tend to adhere to one another when saturated and if added to the concrete in this saturated condition, problems with dispersion arise. For this reason Lam suggests that SAP's be added to the concrete mix in a dry state. Jensen & Lura state that if this is done, care must be taken to ensure that the SAP particles become fully saturated before the setting of the concrete.

2.7.3.1 Influence of SAP's on Compressive Strength

The addition of SAP's changes the microstructure of concrete. Initially, the SAP's particles within the concrete contain water. However, during the hydration process, this entrained water gets consumed leaving air filled voids (Figure 2.20). These additional voids could potentially influence the compressive strength of concrete.

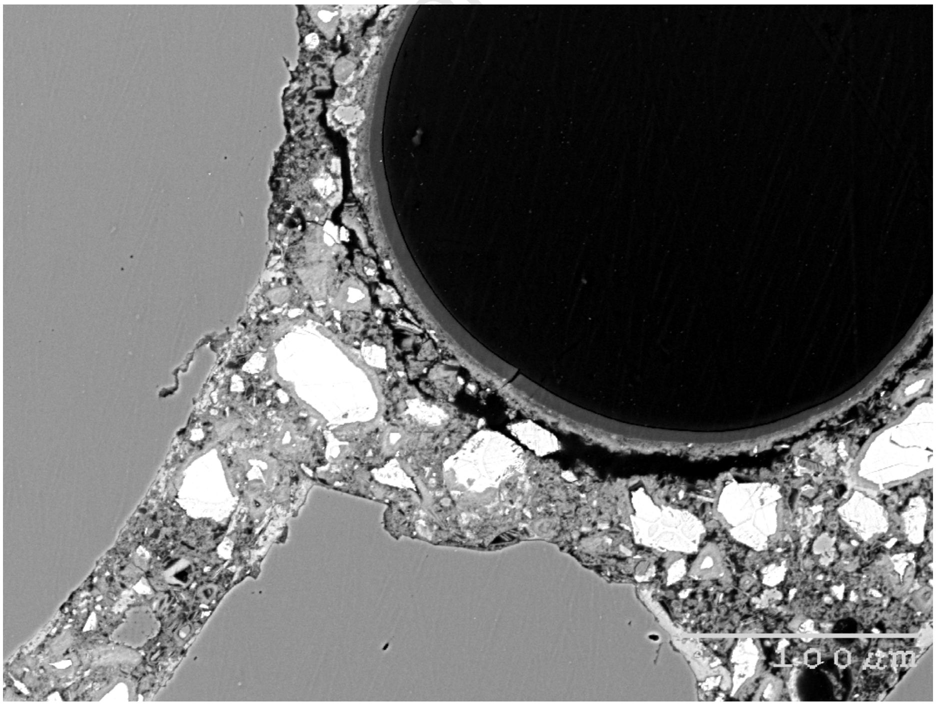

Figure 2-10: A scanning electron image of an air void in a concrete specimen which was previously occupied by a saturated SAP particle. The white area represents the unhydrated cement particles, the grey area the hydrated cement particles and aggregate and the black area the air voids. (Lam, 2005)

Contrasting views exist about the influence of SAP's on concrete compressive strength. Lam (2005) states that the use of SAP's decreases the compressive strength of concrete. Further research suggests that an increase is SAP quantity in concrete reduces compressive strength (Ingarshi *et al,* 2006; Wang *et al*, 2009; Pierard *et al*, 2006). Further research by van der Ham *et al* (2007) showed that at lower w/b ratios, the negative effect of SAP increases.

Conversely, other research suggests that the use of SAP's can increase the compressive strength of the concrete (Jensen & Hansen, 2001; Kovler & Jensen, 2006, Geiker *et al*, 2004). Geiker *et al* (2004) noted that the hydration rate of concrete lowers with a decrease in relative humidity (RH). Geiker (2004) *et al* suggested that the increase in RH over a longer period of time results in a longer period of hydration. This increased hydration period results in more CSH gel being formed, which increased the compressive strength of concrete. This is supported by Kovler & Jensen, who acknowledge that the addition of SAP's can potentially increase the void content within the cement matrix. Kolver & Jensen suggest that a 1% increase in the air content of a concrete specimen will result in a 5% decrease in the compressive strength. However, Kolver & Jensen state that this reduction in compressive strength is outweighed by the gain in compressive strength due to increased hydration of the cement particles.

Research conducted by Monnig & Reinhardt (2006), showed that the addition of SAP's to a concrete mix had no influence on the compressive strength results. Furthermore, research conducted by Lura *et al* (2006) showed that the addition of SAP's did not influence the compressive strength of mortars.

2.7.3.2 Influence of SAP's on Tensile Strength

Lam (2005) states that the use of SAP's increases the tensile strength of the concrete. Conversely, Ingarshi *et al* (2006) and Monnig & Reinhardt (2006) showed that an increase in SAP content resulted in a decrease in tensile strength. Research conducted by van der Ham *et al* (2007) showed that the w/b ratio of a concrete mix influenced the impact of SAP's. van der Ham *et al* (2007) state that the addition of SAP increased tensile strength in concrete with a w/b ratio of 0.5 or more, but decreased tensile strength for concrete with a w/b lower than 0.5.

2.7.3.3 Influence of SAP's on E-Modulus

Very little literature is available regarding the impact of SAP's on elastic modulus. However, van der Ham *et al* (2007)'s experimental work suggested that the addition of SAP's to a concrete mix would decrease the elastic modulus when compared to an equivalent OPC mix.

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2.7.3.4 Influence of SAP's on Autogenous Shrinkage

Literature suggests that the addition of SAP particles to a concrete mix can greatly reduce autogenous shrinkage and restraining stresses. The addition of SAP's reduce autogenous shrinkage in concrete with low w/b ratios (Igarshi *et al*, 2006; van der Ham *et al*, 2007; Lam, 2005; Kovler & Jensen, 2006, Kolver & Jensen, 2007) The addition of SAP's provide an additional water source within the concrete, which prevents self desiccation occurring hence reducing autogenous shrinkage. If a sufficiently large quantity of SAP is added to a concrete mix, autogenous shrinkage can be eliminated completely (Igarshi *et al*, 2006).

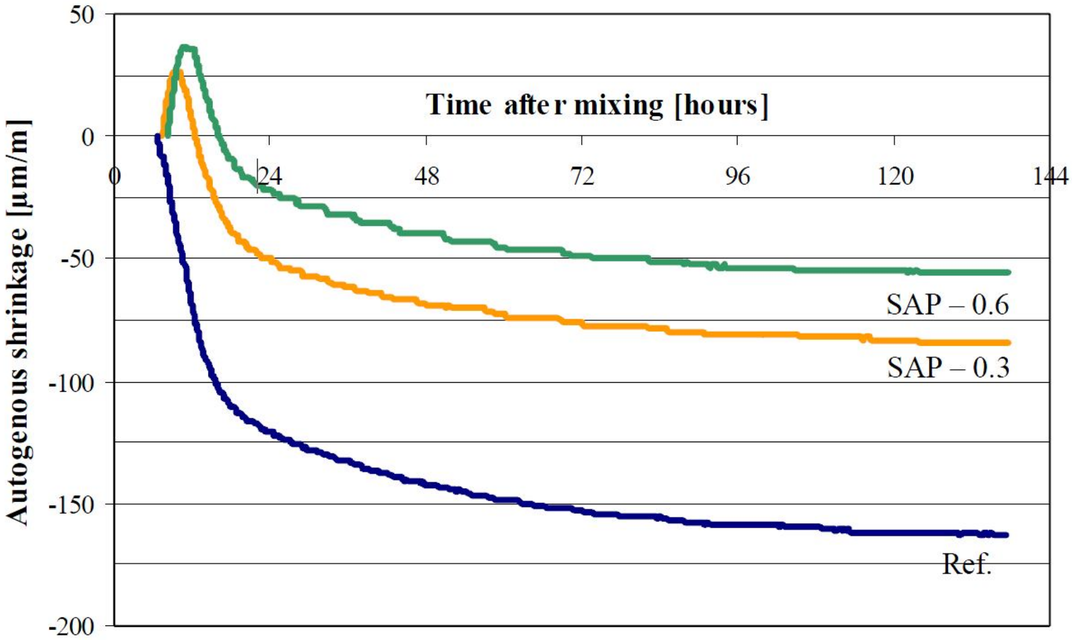

Figure 2-11: Influence of SAP content on autogenous shrinkage (Pierard *et al*. 2006)

The addition of SAP's has the ability to cause concrete to swell. Samples tested by Pierard *et al* (2006) were completely sealed to prevent any shrinkage occurring other than autogenous shrinkage. The results, shown in Figure 2.21 indicate that the addition of 0.3 and 0.6% SAP resulted in the swelling of the concrete samples at early ages. This indicates that autogenous shrinkage was completely prevented by the addition of SAP's.

Literature suggests that the use of SAP's is an effective method to mitigate autogenous shrinkage. However, there is very little research available that addresses both autogenous and drying shrinkage. Drying shrinkage is of concern when dealing with bonded concrete overlays.

2.7.3.5 Influence of SAP's on Drying Shrinkage

Drying shrinkage is of great importance in concrete overlay performance. In order to improve concrete overlay performance, the rate and total drying shrinkage needs to be reduced until the concrete overlay has developed sufficient strength to resist the stresses that result in cracking.

Research conducted by Pierard *et al* (2006) investigated the influence of SAP's on drying shrinkage. The results of their testing are shown in Figure 2.22.

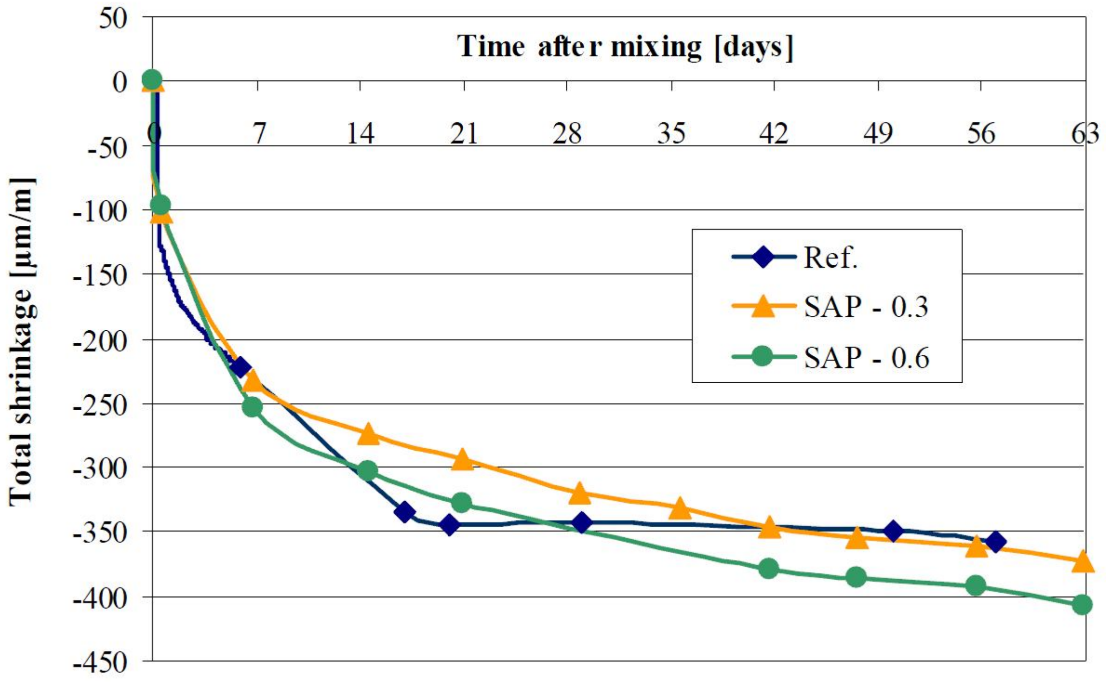

Figure 2-12: Influence of SAP on total shrinkage at 20°C and 65% RH (Pierard *et al*, 2006)

The total shrinkage recorded is a combination of autogenous, chemical and drying shrinkage. The graph shows that the reference and test samples underwent similar total shrinkage. However, the autogenous shrinkage of the samples containing SAP's, shown in Figure 2.21, were lower than the reference sample. This indicates that the drying shrinkage of the samples containing SAP's was larger than the reference sample suggesting that the addition of SAP's increase drying shrinkage. This may be a result of the additional pore structure introduced into the concrete (Pierard *et al*, 2006).

Jensen & Hansen (2001) also researched the effect of internal curing on both autogenous and drying shrinkage. Their results are shown below in Figure 2.23 and agree with the research conducted by Pierard *et al* (2006). Similar to the results discussed in Chapter 2.7.3.4 above, the sealed concrete samples swelled, suggesting no autogenous shrinkage occurred. Figure 2.23 also suggests that an increase in SAP content results in an increase in drying shrinkage. However, the total deformation of the concrete samples tested reduced with an increase in SAP content. This suggests that SAP's can be used to decrease total shrinkage of concrete.

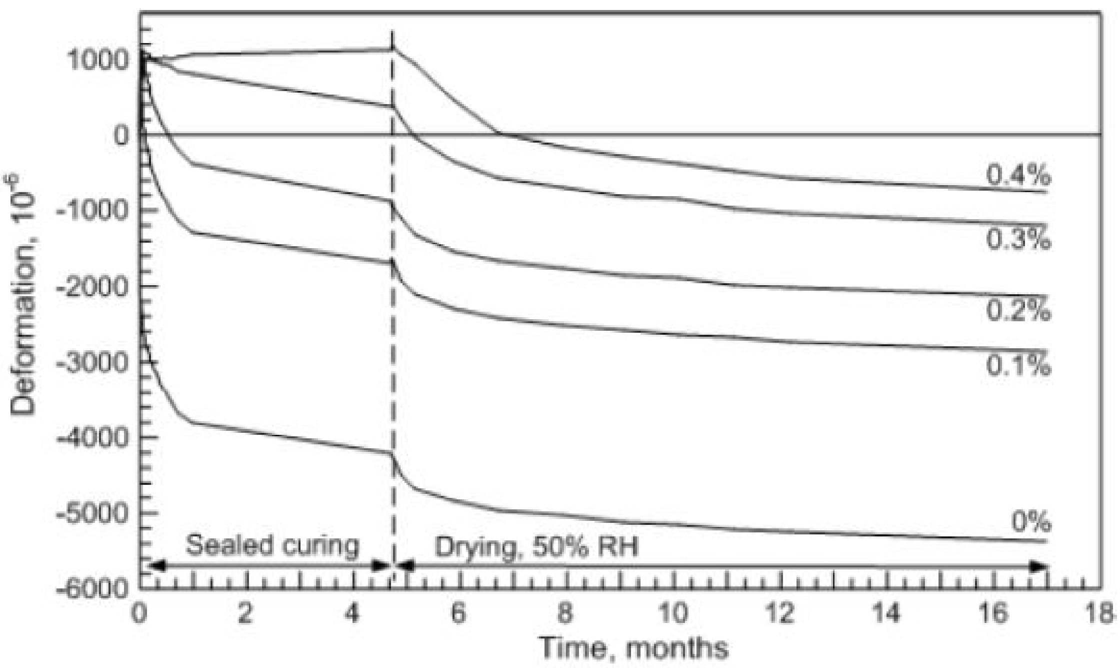

Figure 2-13: Total deformation of concrete samples subjected to both sealed conditions and environmental conditions of 20°C 50% (Jenson and Hansen, 2001).

The similar results were obtained by Mechtcherine *et al* (2006) shown in Figure 2.24. They showed that drying shrinkage increases due to the use of SAP's, although the total shrinkage at 28 days of samples containing SAP's was lower than the control samples due to significant reduction of autogenous shrinkage at early ages.

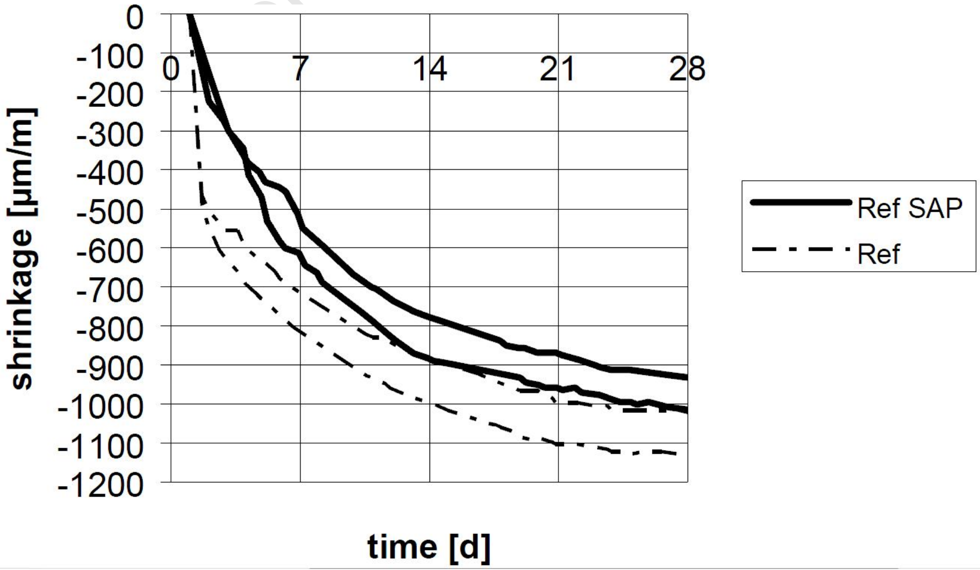

Figure 2-14: Total shrinkage results after 28 days of laboratory expose (Mechtcherine *et al*, 2006)

Research conducted by Monnig and Reinhardt (2006) suggested that while the addition of SAP's increases the drying shrinkage of concrete, the rate of drying shrinkage at early ages decreases. This reduction of drying shrinkage is of importance to concrete overlays as both a reduction in autogenous shrinkage and a decrease in the rate of drying shrinkage at early ages will prevent the concrete overlay from cracking.

2.7.3.6 Influence of SAP's on Creep and Tensile relaxation

Research conducted by van der Ham *et al* (2008) showed that the addition of SAP's to concrete resulted in higher creep factors. The creep factor was calculated using the following formula:

$$\phi\ (t, t_c) = \frac{\varepsilon_c(t)}{\varepsilon_e}$$

where:

$\varepsilon_c(t)$ = deformations after t hours sustained loading
ε_e = elastic deformations

The reason creep factors and not actual creep measurement were used was due to the compressive load applied varying due to it being 40% of the compressive strength. The results of the testing suggest that an increase SAP content results in an increase in creep factor. An increase in creep factor implies that more creep occurs.

van der Ham *et al* (2008) stated that the creep factor and relaxation factor are linked, hence a higher creep factor will result in a higher relaxation factor. This suggests that the addition of SAP's to a concrete mix will result in lower shrinkage stresses developing in hardening concrete and hence a lower probability of cracking.

2.7.3.7 Influence of SAP's on Pore Structure

The addition of SAP's to a concrete mix changes the microstructure of the cement paste matrix. Initially, the SAP particles absorb water into their structure. Some of this entrained water is consumed during the hydration process and lost to drying shrinkage. Once all the entrained water has been consumed, an empty pore remains (Jenson & Hanson, 2001).

However, the addition of SAP particles produce geometrically predesigned macro-pore inclusions at the expense of finer, irregular, partly connected capillary pores. This reduces permeability.

Lura *et al* (2007) showed that the addition of SAP's increased the degree of hydration when compared to samples that do not contain SAP. This view was further substantiated by Igarshi *et al* (2006) who noted that However, it should be noted that the water released from the SAP continued the hydration of cement so that the porosity was decreased, especially in the range of fine capillary pores. Their work also showed that pastes containing SAP's had a lower porosity and more CSH gel than pastes that did not contain SAP's.

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2.7.3.8 Influence of SAP's on Durability

Durability of concrete is a complex property, since a variety of chemical and physical processes may be involved in the deterioration process. However, the permeability or diffusivity of a concrete is very important because, in general, the speed of the deterioration depends on the ease with which the aggressive agent is transported into the concrete. The above reasoning used for the influence of water entrainment on strength can also be applied to permeability and diffusivity. Mathematically, it is possible to show that inclusion of a discontinuous matrix has an inferior influence on the diffusion properties of a material (Jenson & Hanson, 2001). Therefore, durability should generally be improved by replacing finer, irregular, partly connected capillary pores by discrete, spherical inclusions from entrained water, since the connectivity of the pore structure may be of major importance in relation to durability.

2.8 Summary

Concrete overlays have a wide range of uses. During the service life of a concrete structure, general deterioration may occur due to exposure to environmental conditions. If nothing is done to repair the structure, the structure will deteriorate further and not meet its service life requirement. Concrete overlays are often used to rehabilitate and repair concrete structures in order meet its expected service life.

However, concrete overlays often do not perform their required function due to premature failure. Overlay failure can be defined as either premature cracking or debonding. Various factors influence the performance of concrete overlays. These include the composition of overlay concrete, the age of the concrete substrate, the curing procedures followed and environmental conditions such as temperature, wind and relative humidity.

Cracking of bonded concrete overlays will result in the failure of the overlay due to it not meeting its primary requirement of repairing the structure. Cracking of concrete overlays occurs when the tensile stresses that develop within the overlay exceed the tensile strength of the overlay, at which point cracks develop.

One of the driving forces behind crack propagation of concrete overlays is shrinkage. If concrete is allowed to shrink freely, no tensile stresses will develop within the concrete as it can contract evenly. However, the concrete substrate and overlay shrink at different rates. Concrete overlays undergo large quantities of shrinkage, while the older concrete substrates undergo small quantities of shrinkage. These different shrinkage rates result in the development of tensile stresses due to the top surface of the overlay being able to shrink freely, while at the bond between the new and old concrete, the overlay is restrained and cannot shrink freely. These differential stresses may result in cracking.

In order to prevent cracking, the quantity of shrinkage that occurs needs to be minimised. Plastic shrinkage occurs when free mix water within the concrete escapes into the atmosphere due to evaporation. This can be prevented by good curing procedures on site.

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Once concrete transitions from the plastic to the solid state, autogenous and drying shrinkage occurs. Autogenous shrinkage results in the self-desiccation of concrete due to water being used in the hydration reaction. Drying shrinkage occurs when any remaining free water escapes from the capillary pores within the concrete matrix to the environment. This can also be prevented by good curing practice on site.

Another alternative to prevent concrete overlays from cracking is by increasing the tensile strength. This can be achieved by good mix design. By increasing the tensile strength, especially at early ages, the overlay will be able to resist any tensile stresses that develop due to the increased tensile strength.

Tensile relaxation also plays an important role in controlling overlay cracking. Tensile relaxation is the reduction in stress due to imposed strain. Cracking of overlays can be reduced if the rate of deformation is lower than the rate of relaxation. Tensile stresses increase with an increase in rate of shrinkage. Consequently, if tensile strength of concrete is less than tensile stress, concrete will fail unless stresses are relaxed by tensile relaxation. Therefore tensile relaxation may delay the onset of cracking.

The development of good bond strength between the old concrete substrate and the new concrete mortar is important for ensuring the durability of the repaired concrete structure. A good bond allows for the repaired structure to behave monolithically, which reduces both deflections and crack development.

Tensile stresses develop as a result of shrinkage. These stresses develop at the bond between the overlay and the substrate. If there is insufficient bond strength, the edges of the overlay will start lifting, which can lead to the delamination of the overlay, which leads to failure.

Good bond strength can be achieved by good site practices. Effective compaction can help to eliminate the development of air pockets and ensure uniform interfacial bond, hence improve bond strength. Concretes with higher compressive strengths also provide a stronger bond between the overlay and the substrate. Substrate surface preparation can also greatly improve overlay bond strength. Removing all damaged and poor quality concrete using the correct techniques will improve the bond strength. In addition, bonding agents can also be used to improve overlay bond strength.

Adequate curing can greatly improve concrete overlay performance by reducing shrinkage. Internal curing is a relatively new concept that has been used in high performance concrete. However, it has not been applied to concrete overlay technology yet.

Various internal curing methods exist, such as using light-weight aggregates (LWA), internal sealing or superabsorbent polymers (SAP's). A review of the literature available on SAP's suggests that they can be used to overcome some of the problems associated with bonded concrete overlays.

One of the main concerns with concrete overlays is early age shrinkage. At early ages, the stresses developing within the concrete overlay as a result of shrinkage often exceeds the tensile strength of concrete. This can lead to crack propagation. Literature suggests that the addition of SAP's to

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concrete can reduce the total shrinkage that occurs. Various authors have shown that the addition of SAP's can reduce and in some cases completely eliminate autogenous shrinkage.

While literature suggests that the total quantity of drying shrinkage increases slightly due to the addition of SAP's, this shrinkage occurs at later ages. This indicates that the addition of SAP's to concrete reduces the rate of drying shrinkage at early ages. If early age shrinkage is reduced, it will allow concrete to develop sufficient tensile strength to prevent any shrinkage cracking occurring. This will greatly improve concrete overlay performance.

Contrasting views exist about the influence that SAP's have on concrete compressive strength. Some authors argue that the addition of SAP's increase the voids within the cement matrix, which will reduce compressive strength. Other authors suggest that the addition of SAP's result in greater products of hydration, hence a stronger, denser microstructure. An increase in compressive strength can improve overlay performance.

Contrasting views also exist regarding the influence of SAP's on tensile strength. If the addition of SAP's increases tensile strength, early age cracking can be eliminated. SAP's also can also potentially increase the quantity of tensile relaxation occurring, further reducing the chance of cracking. Literature also suggests that the addition of SAP's can improve concrete durability, which will further improve bonded concrete overlay performance.

The beneficial properties of SAP's can potentially improve bonded concrete overlay performance. Vast quantities of research has been conducted into how SAP's can be used to overcome some of the difficulties associated with high performance concrete. However, very little, if any, research exists in how SAP's can influence overlay performance. For this reason, this author proposes to investigate how the addition of SAP's can improve bonded concrete overlay performance. This will form the basis of this thesis.

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3. RESEARCH METHODOLOGY

3.1 Experimental approach

A detailed flow chart of the experimental process is presented in Figure 3.1.

Various parameters were considered in order to determine how the addition of SAP's can improve bonded concrete overlay performance. The design of the repair mortars used in this thesis involved the use of OPC and common cement extenders. The cement extenders used were ground granulated blastfurnace slag (GGBS), fly ash (FA) and silica fume (SF). Water:binder ratios of 0.45 and 0.55 were used.

Jenson and Hanson suggest that the optimum quantity of SAP to use is 0.3% of the total binder content. However, very little literature is available regarding how the addition of SAP's influence the characteristics of cement extenders. For this reason, the quantities of SAP used were 0%, 0.2%, 0.4% and 0.6% of the total binder content. A total of 24 different mixes were to be tested.

A large number of tests needed to be performed in order to determine the influence SAP's had on concrete overlay performance. Due to time constraints, all the proposed test methods could not be performed on all 24 mixes. For this reason, testing was divided into 2 stages. Initial testing involved all 24 mixes being subjected to compressive strength, tensile strength and durability tests. The results of the tests were analysed and compared in order to determine which mixes performed optimally. These mixes would be subjected to further testing.

The mixes containing SF outperformed the other mixes. These mixes were analysed and optimised. A total of 8 different mixes were subjected to additional testing. These tests included tensile strength tests, tensile relaxation, shear bond strength, free shrinkage, restrained overlays, elastic modulus, carbonation and bulk diffusion tests were performed. The results were analysed in order to determine how the addition of SAP's influenced bonded concrete overlay performance.

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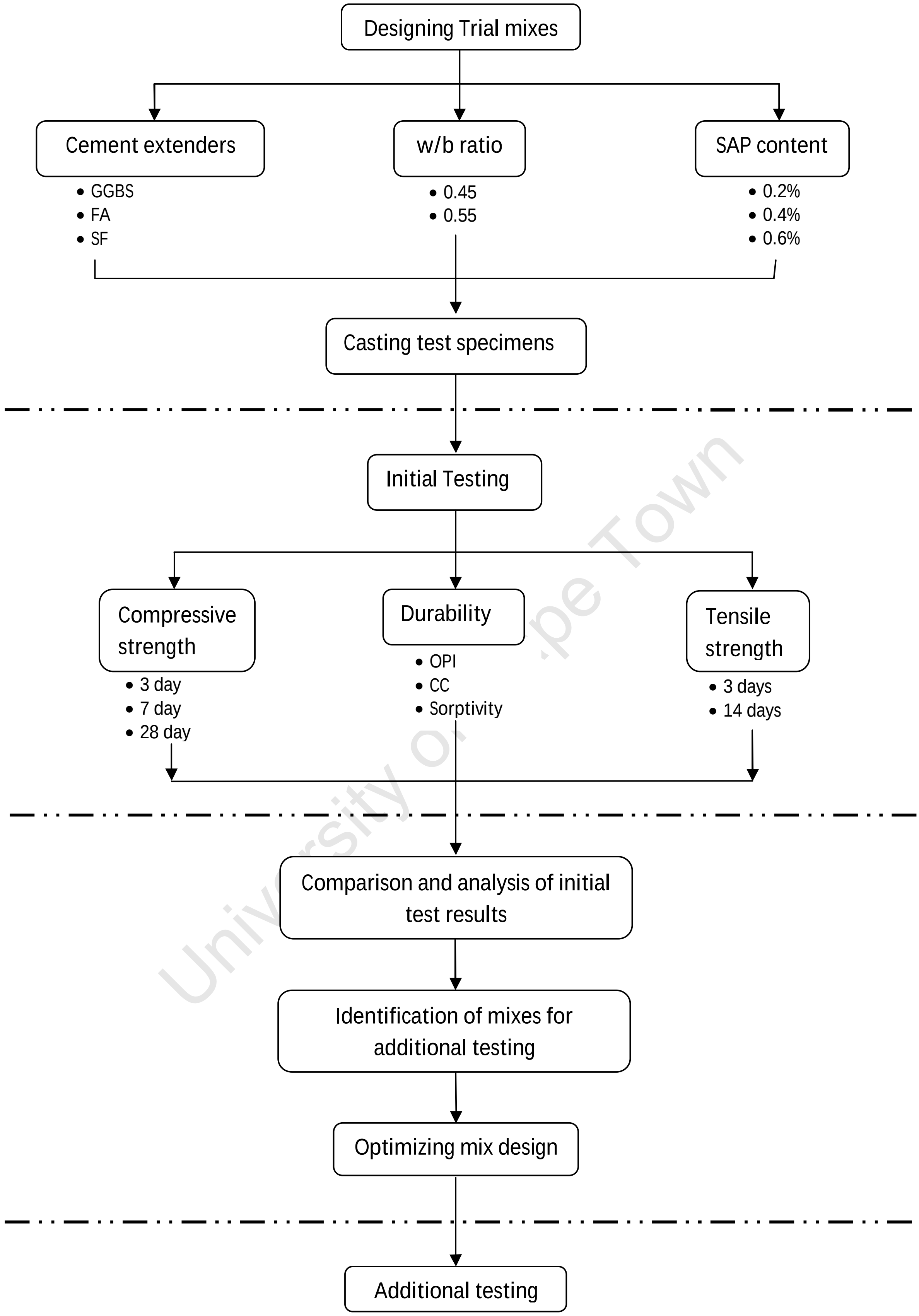

Figure 3-1: Structure of experimental research

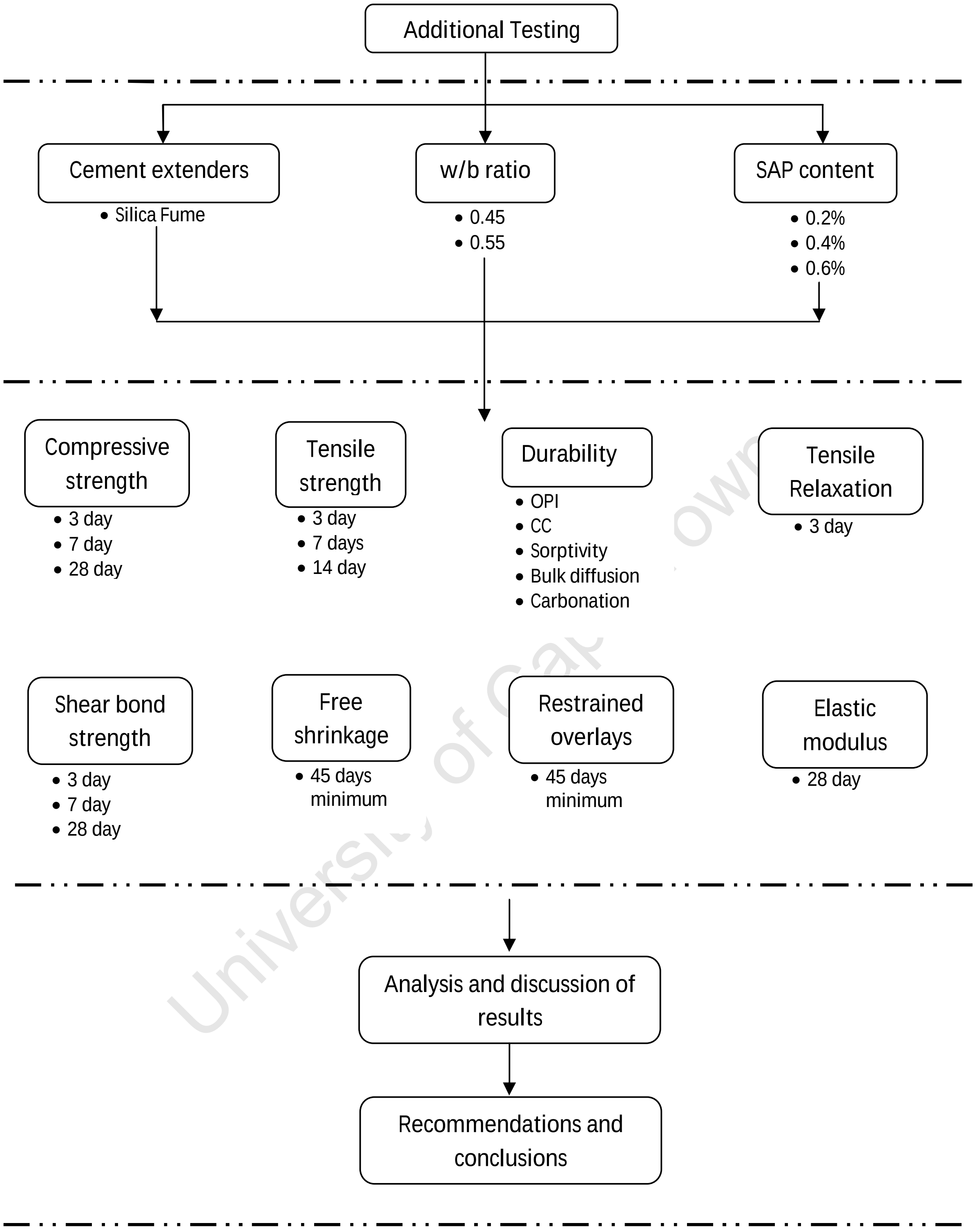

Figure 3-1: Structure of experimental research (continued)

3.2 Experimental Techniques

3.2.1 Introduction

There is limited information available in literature about the use of SAP's in concrete overlays. For this reason, this study will rely on experiments in order to get satisfactory indications or conclusions regarding the beneficial or detrimental effects of using SAP's as an additional mix component for bonded concrete overlays.

This chapter will discuss the mix design of the repair mortars used in this research as well as the properties of the materials used. The test variables and the reasons for their selections will be specified as well as the thought process behind all the testing involved in this research. The test methods used in this research will also be discussed. A total of 24 different mixes were to be tested. Due to time constraints, all 24 mixes could not be subjected to all the proposed test methods. For this reason, testing was divided into 2 phases. Initially, all 24 mixes would be subjected to compressive strength, tensile strength and durability testing. Upon completion, the results were analysed and the best performing mixes were identified. These mixes were then optimised and additional testing was conducted on these mixes only.

3.2.2 Test Variables

3.2.2.1 Water Binder (w/b) ratio

Figure 5.1 shows the assumed effects of w/b on compressive and tensile strength, elastic modulus, shrinkage and relaxation. Two w/b ratios were tested: 0.45 and 0.55. This generally covers the range of normal concretes that may be used in overlays.

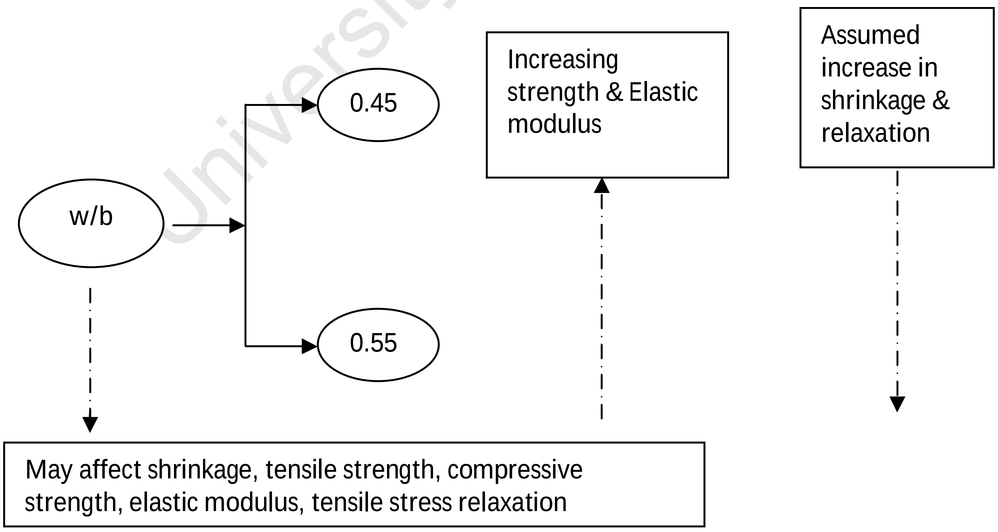

Figure 3-2: Assumed influence of w/b ratio on various parameters

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3.2.2.2 SAP content

An increase in SAP content reduces the quantity of free mix water available in concrete, which reduces durability. This was clearly visible during the trial mixes, where samples containing a larger quantity of SAP had no bleed water present on the surface after casting. The decrease in workability was also observed during casting, where samples with a larger SAP content were more difficult to transport, cast and compact due to an increase in stiffness of the mix. This decrease in workability directly influences the quantity of SAP that can be added to concrete.

The quantity of SAP used is measured as a percentage of the total binder present within the concrete/mortar. Literature suggests that the optimum quantity of SAP to be used is between 0.35 and 0.4% of the total binder. For this research, the quantity of SAP used in the various mixes was set at 0%, 0.2%, 0.4% and 0.6%.

3.2.2.3 Cement Extenders

Literature shows that SAP's can be used in conjunction with cement extenders. However, insufficient literature is available regarding the influence of cement extenders used with SAP's in concrete overlays. For the initial, samples containing ground granulated blastfurnace slag (GGBS), condensed silica fume (SF) and fly ash (FA) were used as cement extenders along with ordinary Portland cement (OPC). The extenders were used in the following proportions: 70:30 OPC: FA, 50:50 OPC: GGBS and 90:10 OPC: SF.

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3.2.3 Mix Design and Materials

3.2.3.1 Cement

The cement used in this research was a CEM I OPC 42.5N provided by PPC.

3.2.3.2 Sand

Klipheuwel sand was used as the fine aggregate in all of the test mixes. Klipheuwel sand is found locally in Cape Town and has a good grading. It has properties that include good workability and a low water demand. A grading curve for the sand used in this research can be found in Figure 3.3 below.

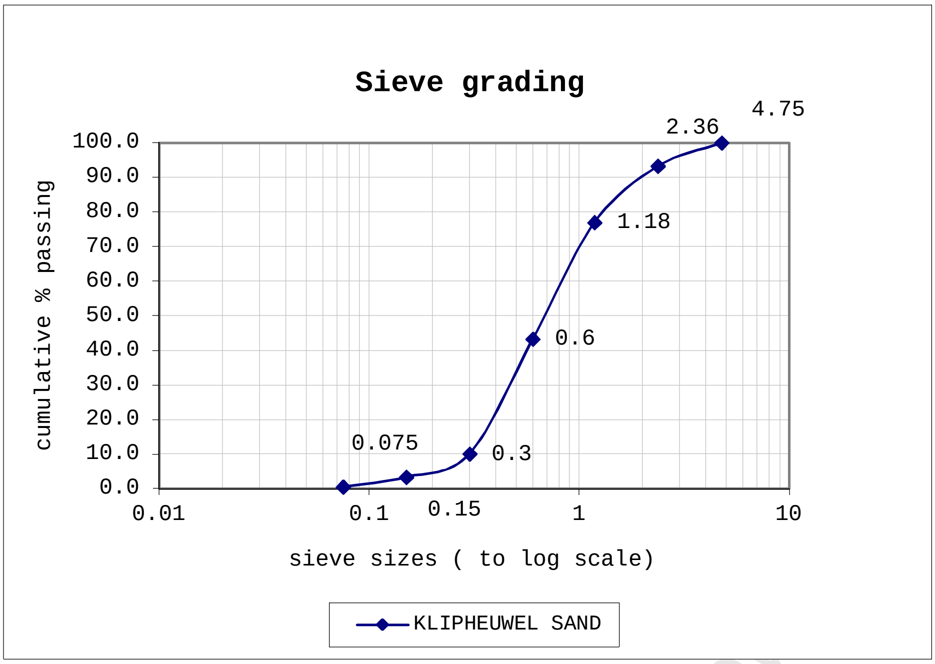

Figure 3-3: Grading curve of Klipheuwel sand used in this research

All the sand used in this research was dried in an oven at 50°C for a period of 48 hours. This was to ensure that the sand was completely dry and that no additional water other than the mix water was present.

3.2.3.3 Admixtures

The addition of SAP's to concrete reduces the concrete's workability. This is due to the SAP absorbing most of the free bleed water hence reducing workability. In order to overcome this, a powdered superplastizer was used. Powercon 100 HS, provided by BASF, was used as a superplasticizer for all samples containing SAP's in this research. Sika ViscoCrete was used as a superplasticizer for all the control samples.

3.2.3.4 Curing regime

The curing conditions for this research were kept constant for all samples. In order to determine the benefits of using internal curing using SAP's, limited external curing was used. Once the samples were cast and demoulded, all samples were kept under plastic sheeting for a total of 3 days. This was done in to simulate site conditions.

After 3 days of curing using plastic sheeting, the samples were then placed in a conditioning room kept at a constant temperature of 23 ±2 °C and a relative humidity of 65± 5% until tested. However, the restrained overlays cast onto the laboratory floor were exposed to environmental conditions at approximately 20-30°C and 70% RH.

3.2.4 Mortar Mix Design for initial testing

A total of 24 repair mortars were tested. The mixes consisted of two w/b ratios (0.45 and 0.55) and three different binder combinations of OPC, FA, GGBS and SF. As the primary focus of this work is on repair overlays, which generally occur in aggressive environments requiring highly durable concrete,

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no mixes consisting of pure OPC were studied. To increase durability, all concrete mixes consist of a blend of binders – either OPC and FA, OPC and GGBS or OPC and SF. The general mix designs are shown in Table 3.1.

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Table 3-1: General mix designs for 1m^3 of concrete

Mix	w/b	Total Binder	CEM 1	Fly Ash	GGBS	SF	Water	Sand Content	SAP Content	Slump	Superplasticizer
		kg	kg	kg	kg	kg	kg	kg	kg	mm	kg
1	0.45	556	389	167	-	-	250	1490	1.11	60	0.25
2	0.45	556	389	167	-	-	250	1490	2.22	50	1.18
3	0.45	556	389	167	-	-	250	1490	3.33	40	1.76
4	0.45	556	278	-	278	-	250	1490	1.11	40	1.25
5	0.45	556	278	-	278	-	250	1490	2.22	40	2.35
6	0.45	556	278	-	278	-	250	1490	3.33	40	3.53
7	0.45	556	500	-	-	56	250	1490	1.11	40	1.00
8	0.45	556	500	-	-	56	250	1490	2.22	50	1.76
9	0.45	556	500	-	-	56	250	1490	3.33	40	2.94
10	0.55	455	318	136	-	-	250	1530	0.91	90	-
11	0.55	455	318	136	-	-	250	1530	1.82	70	-
12	0.55	455	318	136	-	-	250	1530	2.73	80	0.59
13	0.55	455	227	-	227	-	250	1530	0.91	60	-
14	0.55	455	227	-	227	-	250	1530	1.82	60	0.59
15	0.55	455	227	-	227	-	250	1530	2.73	50	2.06
16	0.55	455	409	-	-	45	250	1530	0.91	70	0.25
17	0.55	455	409	-	-	45	250	1530	1.82	50	0.59
18	0.55	455	409	-	-	45	250	1530	2.73	50	2.35
					Controls						**litres**
19	0.45	556	389	167	-	-	250	1490	-	60	-
20	0.45	556	278	-	278	-	250	1490	-	30	1.76
21	0.45	556	500	-	-	56	250	1490	-	80	2.35
22	0.55	455	318	136	-	-	250	1530	-	150	-
23	0.55	455	227	-	227	-	250	1530	-	50	0.59
24	0.55	455	409	-	-	45	250	1530	-	50	0.59

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The slump test as described in SABS Method 862-1:1994 was used to measure the slump and assess the consistence and workability of the concrete mix designs. The addition of SAP's reduced the workability of the mixes substantially by absorbing most of the free bleed water. In order to account for this, a powdered superplasticizer was added until each mix had a minimum slump of 40 mm.

3.2.5 Initial Test Parameters Considered

The concept of using SAP's in concrete overlays is a relatively new concept and this author could find no current literature covering the use of SAP's in repair materials. However, extensive research is available about the potential benefits of using SAP's in other applications within the field of concrete technology. For this reason, extensive testing of the use of SAP's in concrete as a repair material was required.

24 mixes were to be initially tested in this research. However, due to the large number of tests required and the large number of samples requiring testing, this process needed to be optimized. Specific tests were conducted in order to determine how repair mortars containing SAP's performed and the results of each test were compared in order to determine which repair mortars benefited the most from the addition of SAP's. Compressive strength, tensile strength and durability testing, based on the UCT durability index tests, were used to compare the performance of the various samples.

3.2.5.1 Compressive Strength

Compressive strength testing was chosen as it is an industry standard. Literature was inconclusive as to how the addition of SAP's influenced compressive strength. The compressive strength of a material is also an important factor in determining the materials used. If the material doesn't meet the required compressive strength value, it cannot be used for certain applications.

Compressive strength testing involves a simple, quick process and the results are instantly available after testing. This allowed for all the samples to be cast and tested in a short period of time and provided a quantitative way of comparing the large number of test mixes.

Three 100 x 100 100 mm cubes were crushed at 3, 7 and 28 days of age. These ages were chosen as the early age properties of repair mortars are the most critical in determining how they will perform as a large quantity of the problems associated with bonded concrete overlays appear at early ages. Testing was conducted according to SANS 5863:2006.

3.2.5.2 Tensile Strength

The tensile strength of concrete overlays is an important characteristic, especially at early ages. Large quantities of tensile stresses develop within the concrete overlay as a result of restrained shrinkage, differential humidity gradients, insufficient tensile relaxation and various other factors. If the tensile strength of the repair overlay does not exceed the tensile stresses that develop, the repair overlay will crack. This will result in the repair overlay not performing its required function.

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The tensile strength testing was performed on a Zwick Roell (Z020) Universal Testing Machine (UTM). Dogbone samples, as show in Figure 3.4, were subjected to a uniaxial tensile force until failure. For the initial testing, samples were tested at 3 and 14 days of age. The exact same method of testing was used as in the research conducted by Masuku (2009). The details of the tensile strength test method can be found in his research.

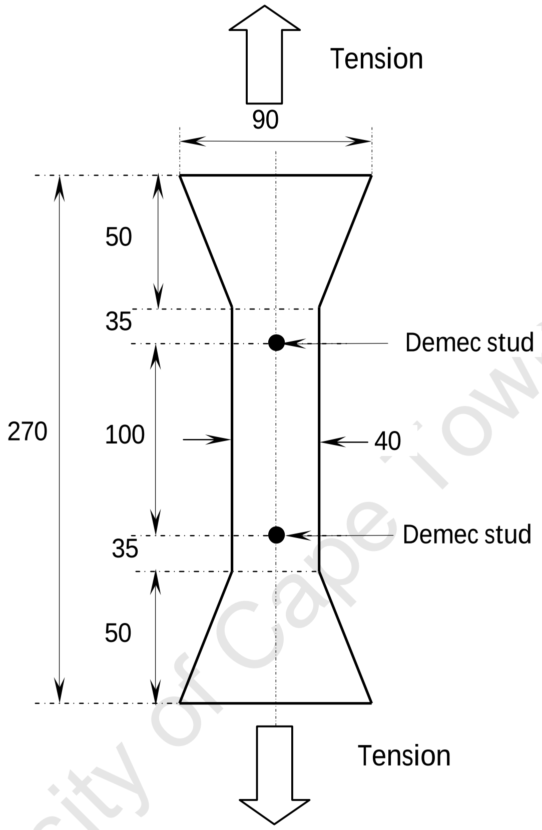

Figure 3-4: Geometry of test specimen (dimensions in mm)

3.2.5.3 Durability

The durability of the repair mortar was also an important consideration. If a repair mortar is not durable, it will not be able to prevent aggressive agents entering the structure and further corrosion and degradation of the structure will occur. This will result in the failure of the repair mortar as it will not be performing its primary function.

Literature suggests that the addition of SAP's to concrete affects its permeability. This in turn could reduce the durability of the repair mortar, depending on the connectivity of the pores left behind by the SAP. The influence of SAP's on the durability of the repair mortars used in this research was tested according to the UCT Durability Index (DI) test methods. Sample durability is classified according to Table 3.2. The details of UCT durability index tests are explained below.

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Table 3-2: Durability classification based on the UCT DI prediction tests

Durability Class	OPI (log scale)	Sorptivity (mm/h^{05})	Conductivity (mS/cm)
Excellent	> 10.0	< 6	< 0.75
Good	9.5 – 10.0	6 -10	0.75 – 1.50
Poor	9.0 – 9.5	10 – 15	1.50 – 2.50
Very Poor	< 9.0	> 15	> 2.50

Oxygen Permeability Index (OPI)

Samples were prepared and tested according to UCT Durability Index (DI) test methods. The details of the OPI test method can be found in UCT Durability Index Manual, Version 1.0 (2009). The results of the OPI test give a measure of the permeability of oxygen through a concrete sample. This permeability value is then related to the ingress of carbon dioxide into the sample. A carbonation prediction model, developed by Alexander and Mackechnie (2000), can predict the carbonation depth of the sample at various ages based on this OPI value. The higher the OPI value, the greater the carbonation resistance of the sample tested.

Chloride Conductivity (CC)

Samples were prepared and tested according to UCT Durability Index (DI) test methods. The details of the CC test method can be found in UCT Durability Index Manual, Version 1.0 (2009). The chloride conductivity value is used as a basis to predict the chloride penetration into a sample, based on the South African chloride ingress prediction model developed by Alexander and Mackechnie (2000). The lower the chloride conductivity value, the greater the chloride resistance of the sample tested.

Sorptivity

Samples were prepared and tested according to UCT Durability Index (DI) test methods. The details of the CC test method can be found in UCT Durability Index Manual 2009, Version 1.0 (2009). Sorptivity testing is used to measure the water permeability of a sample and the sorptivity and porosity of the sample can be calculated from the results.

3.2.6 Reanalysis of Mix Design, Mix Optimization and further testing

The results of the initial testing were used as a method of comparing how the addition of SAP's influenced the performance of the various mixes tested. If necessary, the initial mixes tested were to be altered in order to improve their performance. Based on the results of the initial testing, the number of mixes subjected to further testing were reduced. The additional tests were used to further assess the performance of repair mortars containing SAP's. The additional tests are described below.

3.2.6.1 Free Total Shrinkage

Separate samples for free shrinkage strain were cast. Specimen dimensions were 50 x 50 x 300mm as shown in Figure 3.5. Demec targets were attached on two sides of a sample along the specimen

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length within the prismatic section at 100 mm gauge length. This was in order to measure free shrinkage strains within the prismatic section. Free shrinkage specimens were placed in an environment room and strain was measured and recorded for a minimum of 50 days.

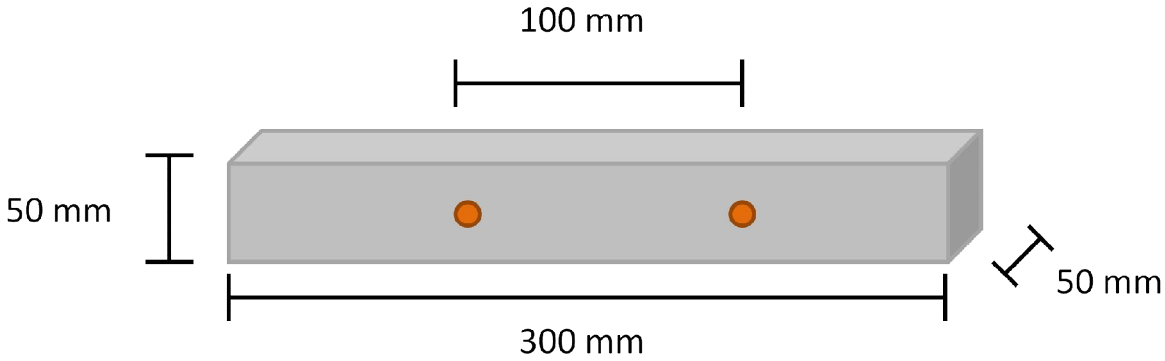

Figure 3-5: Schematic of samples used for total free shrinkage testing

Free shrinkage samples were cured under plastic for 3 days prior to testing. Thereafter they were placed in an environment room at 23 ±2 °C and kept at a RH of 65 ± 5%. Samples were unsealed on all surfaces. This was in agreement with Beushausen and Alexander (2006) who argued that completely unsealed specimens best represent the boundary conditions experienced in actual overlays. Bonded overlays may not only lose moisture through exposed surfaces to the environment. Moisture loss may also occur through the substrate. If the substrate is relatively dry, it tends to absorb water from the overlay.

Asad *et al* (1997) and Vaysburd *et al* (2000) used specimens that were predominantly exposed to one dimensional moisture loss i.e. other faces were sealed to avoid moisture loss in transverse directions. This was disregarding effects of substrate absorption. This may result in underestimating shrinkage strains.

In this study, strains were measured using an extensometer with a gauge length of 100 mm and measuring accuracy of 10 microstrain. Strain data was collected daily for the first 14 days after curing under plastic, then every alternate day.

3.2.6.2 Restrained Shrinkage

Overlays were cast on a portion of the concrete laboratory floor in order to give a qualitative assessment of how each overlay performed. The laboratory floor was jack hammered in order to provide a better bonding surface and to simulate site conditions. The substrate was then cleaned and wetted for a period of 24 hours. The substrate surface was then exposed to environmental conditions until it was surface dry. Figure 3.6 shows the final prepared surface. It was assumed that the base slab was infinitely rigid as it was part of the existing slab within the laboratory.

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Figure 3-6: Concrete substrate after jack hammering, cleaning and wetting for 24 hours.

Each repair overlay had dimensions of 1200 x 300 x 40mm and was cast onto the rigid concrete base, as shown by Figure 3.7. These slender dimensions were selected to ensure that the overlays would crack. The samples were cured under plastic for 3 days and then exposed to the laboratory conditions with a temperature range between 20-30°C and an RH of approximately 70%. The overlays where inspected and assessed daily for cracking.

Figure 3-7: Overlays cast onto the infinitely rigid laboratory floor

3.2.6.3 Shear Bond Strength

The modified FIP test developed by Beushausen and Alexander (2007) was used to test the shear strength of the specimens. The shear bond specimen consists of a 150 x 150 x 75mm substrate with a 75 mm overlay, allowing for the use of standard 150 mm cubes. The modified FIP test theoretically prevents bending moments and tensile forces at the interface, allowing pure shear force to develop. The schematics of the load application and the interface shear stresses which develop are shown in Figure 3.8. Figure 3.9 shows the test setup on a specimen and the detailed dimensions of the test equipment are provided in Appendix A.

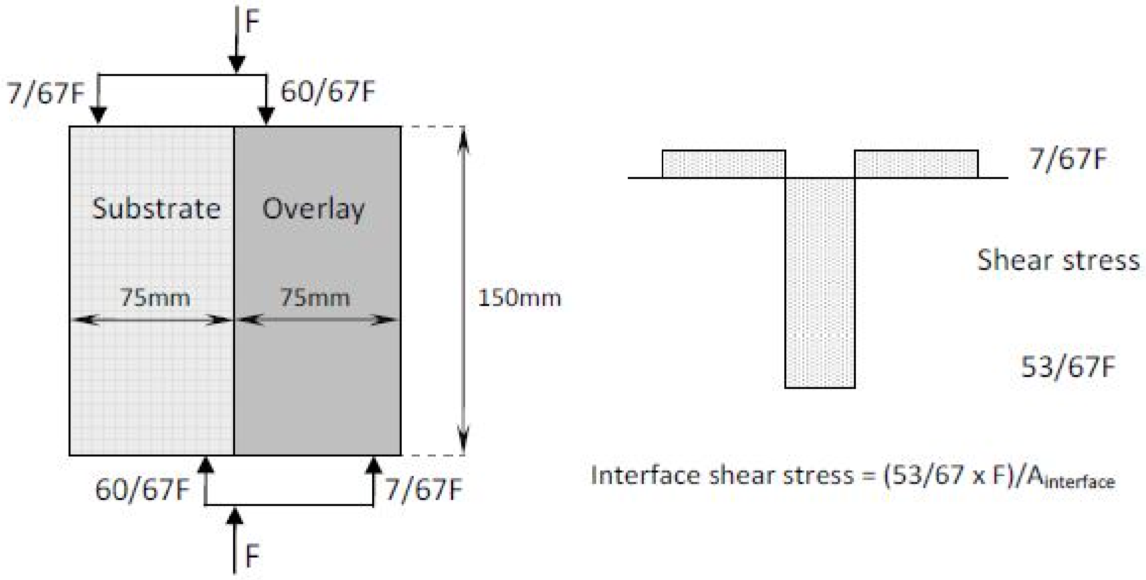

Figure 3-8: Schematics of load application and induced interface shear stress for the modified FIP test

The bond strength tests were conducted on specimens at ages of 3, 7 and 28 days. Six specimens were cast for each combination of parameters to allow for the large scatter of results characteristic of the test method. The shear bond strength was then calculated using the formula shown in Figure 3.8.

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Figure 3-9: Photograph of the test setup for the modified FIP shear bond test (Cloete, 2008)

Substrate concrete for shear bond testing

The same concrete mix design was used for all substrate concrete specimens for shear bond testing. A concrete mix with a target strength of 40 MPa was designed using conventional, locally available materials in order to mimic concrete repair on typical existing structures. Crushed Greywacke of 19 mm nominal maximum size, typically used for concrete construction in the Cape Peninsula in South Africa, was chosen as the coarse aggregate. Klipheuwel sand, which is a siliceous pit sand with good particle shape and continuous grading, was chosen because of its relatively high content of coarse aggregate particles. The latter provided a sound and rough interface texture using sandblasting for interface preparation. The substrate concrete properties are found in Table 3.3.

Table 3-3: Mix design and properties of the substrates used

Substrate concrete: Mix design and material properties		
Cement CEM I 42.5	kg/m^3	350
Water	kg/m^3	175
19 mm Greywacke	kg/m^3	1025
Klipheuwel sand	kg/m^3	875
w/b ratio	-	0.5
Slump	mm	90±20
28 day Compressive Strength	MPa	48.4
28 day Elastic modulus	GPa	28.1
Porosity	%	8.1
Sorptivity	$mm/h^{0.5}$	10.8

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Substrate surface preparation

Sandblasting the concrete substrate is one of the most common methods for provision of a sound and rough interface for concrete repair works and was, therefore, adopted for the interface surface profile in this project. The original surface of the freshly cast beams was finished smooth using a steel float. The beams were sandblasted at an age of approximately 28 days exposing aggregates. Due to the originally smooth surface of the beams, the sandblasted interfaces had virtually no surface profile, i.e. the overall surface texture of the substrate beams was relatively smooth. The average surface roughness of all specimens, measured with the Sand-Area Method (Kaufmann, 1971), was 0.7 mm. Figure 3.10 shows a typical sandblasted surface.

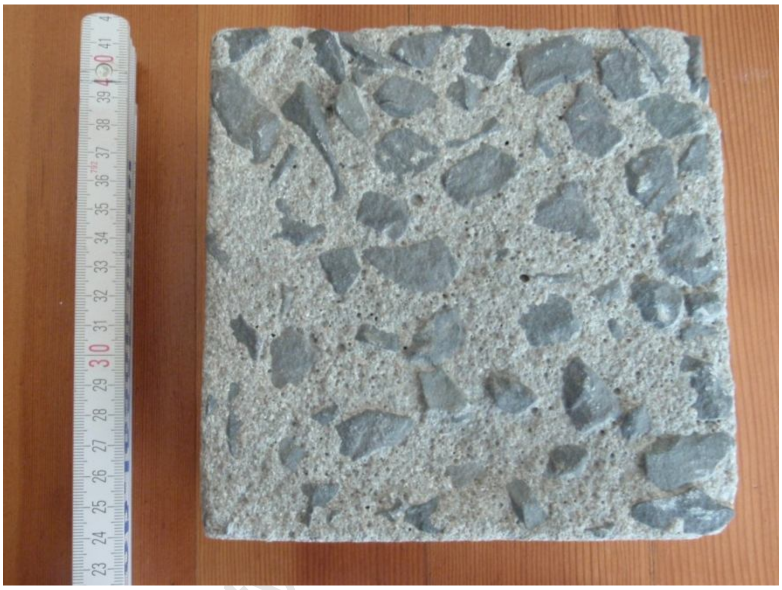

Figure 3-10: Sandblasted surface of substrate

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Substrate Moisture Condition

Various opinions exist as to how the moisture condition of the substrate influences the bond between the substrate and the overlay. These are discussed in detail in Section 2.3.3.4. For this research, substrates were cast and wet cured for a period of 14 days. They were then exposed to laboratory conditions.

The bond surfaces of the substrate were pre-wetted and then exposed to laboratory conditions before overlay casting. Once the bond surface was dry to the touch, overlays were cast onto the substrate. This was done to ensure similar substrate conditions for both the shear bond test samples and the restrained overly samples. Overlays were cast onto the substrates at an approximate substrate age of 42 days.

3.2.6.4 Tensile Relaxation

Tensile relaxation tests were conducted on dogbone samples. Samples were cast and cured for 3 days under plastic and then tested. The amount of possible tensile relaxation decreases with sample age. This research is particularly interested in the early age performance of repair overlays and for this reason all samples were tested at an age of 3 days. Only one testing age was considered due to time constraints. Three samples per mix were subjected to relaxation testing. Details of the testing considerations and method are explained below.

Test duration

Samples were tested at 3 days of age. Literature suggests that tensile relaxation tests should last a minimum of 72 hours (Masuku, 2009). However, due to time constraints, a testing duration of at least 24 hours was selected for relaxation testing. This short testing cycle was suggested due to the majority of tensile relaxation occurs at early ages.

Testing procedure

After samples had been cast and cured under plastic for 3 days, they were removed and cleaned thoroughly before testing. All tensile relaxation samples were tested under sealed conditions. This was done in order to avoid simultaneous drying shrinkage. Sealed tests are best represented by assuming that shrinkage strain is insignificant. Sealing was done by applying a paraffin wax coating. All six exposed surfaces of test samples were sealed in order to prevent moisture loss during testing. As a result, there were no additional strains on the specimen due to drying shrinkage. This enabled tensile relaxation to occur at constant strain.

For the purposes of this research, tensile relaxation samples were subjected to 75% of their tensile strength capacity. Literature suggests that relaxation tests should be conducted at 80% of sample tensile strength. However, due to time constraints, the author did not want to risk failing any samples due to overloading.

Tensile relaxation tests were performed under constant strain. In the absence of an automatic strain monitoring device, tests were performed under a displacement-control mode. This meant that total crosshead travel of the machine was measured. For this reason, the strain output from the UTM was a measure of the distance moved by the crosshead including the strain in the specimen.

Test specimens were inserted into gripping jaws and then held in position within the testing frame. Test data was stored and displayed locally on a computer. Therefore, as the specimen was loaded, stress within the member would decrease with time. A decreasing stress curve was visible on the computer display.

3.2.6.5 Elastic Modulus

Elastic Modulus in compression was determined from tests on 200x100x100 mm prisms. Due to time constraints, samples were only tested at a sample age of 28 days. Bonded overlays are subjected to differential shrinkage and commonly experience tensile stress. For this reason, the modulus in tension is of greater significance than that in compression. However, the two can generally be considered to be similar (Neville, 1995) and the measured modulus of elasticity in compression was therefore used in the analysis of tensile overlay stress.

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3.2.6.6 Carbonation Testing

The rapid carbonation test involves placing specimens in a carbonation chamber with high concentrations of CO_2, 100 or more times the concentration of the atmosphere. The atmosphere has about 0.03% to 0.04% of carbon dioxide. These numbers vary slightly and have been increasing over the last decades. For the purposes of this research, the carbon dioxide concentration within the chamber was set at 4% carbon dioxide, which is roughly 100 times that of the atmosphere. The relative humidity within the chamber was kept between 65-70% for the duration of the testing.

Four 100 x 100 x 100 mm cubes per mix were exposed to the above mentioned conditions for a period of 42 days. All 4 samples were tested at this age. The samples were then cut in half and the ingress of the carbonation front was measured. Only one sample age (42 days) was considered as this test was used as a qualitative measure of how an increasing quantity of SAP influenced the ingress of CO_2.

3.2.6.7 Bulk Diffusion Testing

The aim of this Scandinavian test method is to determine the apparent chloride diffusion coefficient and the projected surface chloride-ion concentration of various concrete samples based on the ASTM International design code (ASTM C1556). Samples are cored, cleaned and sealed before being placed in various calcium hydroxide and sodium chloride solutions for specific time periods. After the set exposure time, samples are removed and thin layers of concrete are ground off parallel to the finished surface.

The chloride content of each of these layers is then determined. Fick's second law diffusion is then used to calculate the apparent chloride diffusion coefficient of each sample, which is a measure of the chloride resistance of the concrete (Gardner and Beushausen, 2006).

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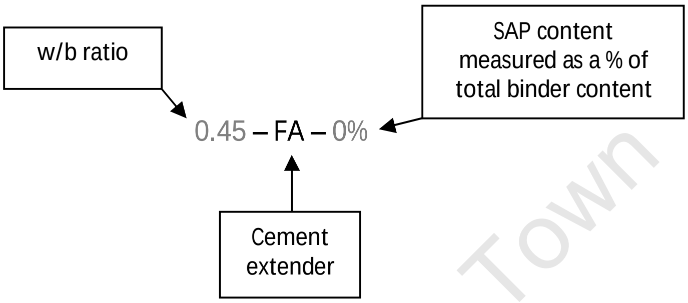
4. RESULTS OF TESTING

4.1 Results of Initial Testing

As discussed in Chapter 3.2.5, three methods of comparison were originally used to assess the performance of the initial mixes. The tests used were compressive strength, tensile strength and durability based on the UCT DI tests. The results are shown and discussed below.

The test specimens have been labelled on all relevant graphs and tables in such a way that all information about the w/b ratio, cement extender and quantity of SAP used can be seen without referring to previous tables. The following nomenclature was used:



A summary of the abbreviations used are as follows:

FA – Fly Ash
GGBS – Ground Granulated Blastfurnace Slag
SF – Silica Fume

4.1.1 Compressive Strength Results

The testing ages used in this experimental research were 3, 7 and 28 days. The results are shown in Figures 4.1 – 4.6.

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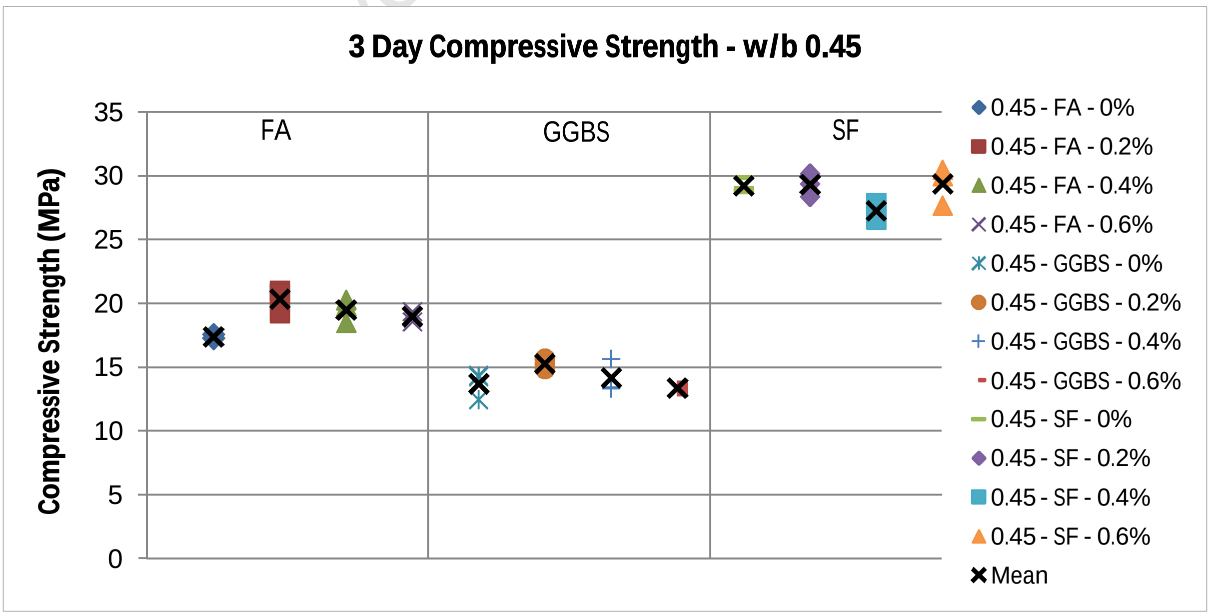

Figure 4-1: 3 day compressive strength results of initial mixes with a w/b of 0.45

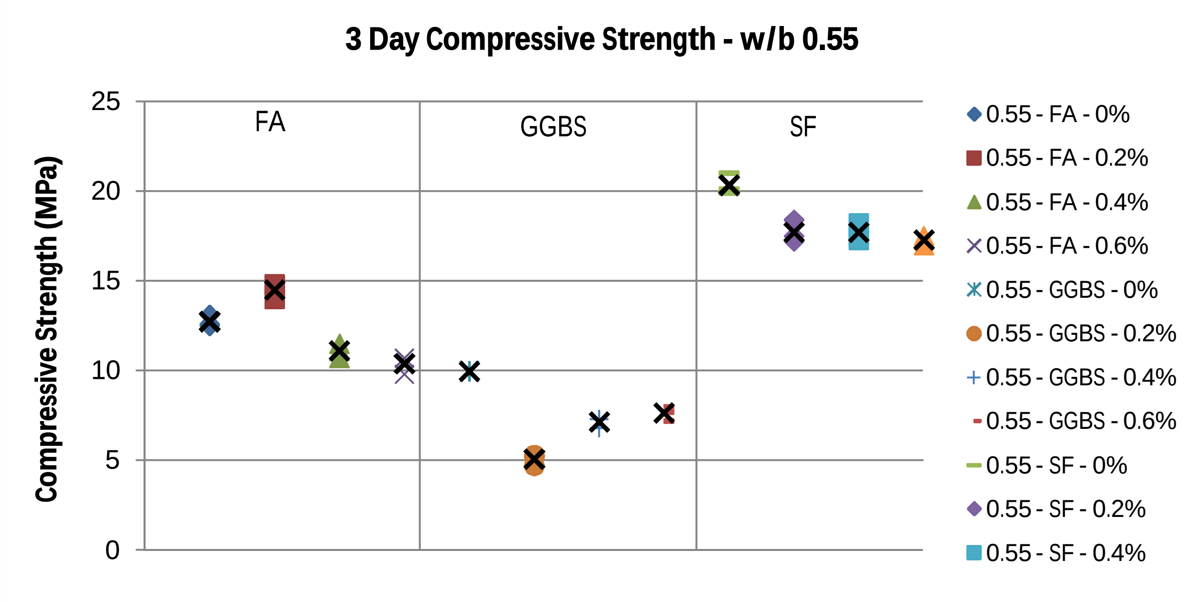

Figure 4-2: 3day compressive strength results of initial mixes with a w/b of 0.55

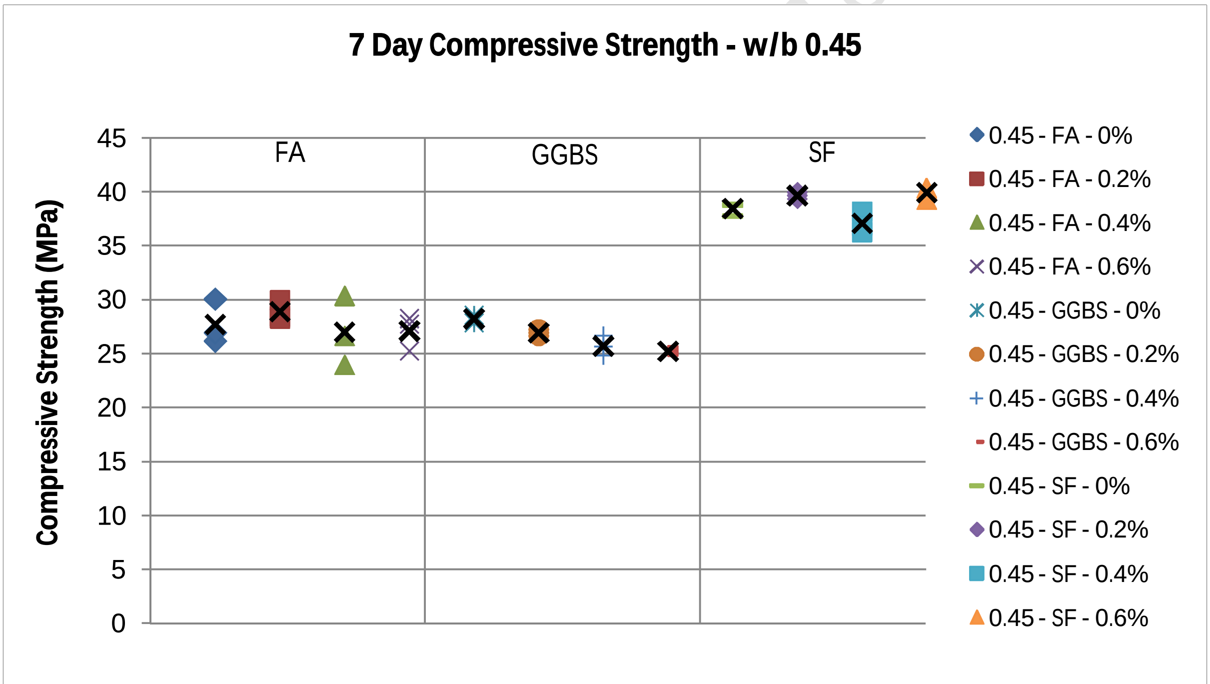

Figure 4-3: 7 day compressive strength results of initial mixes with a w/b of 0.45

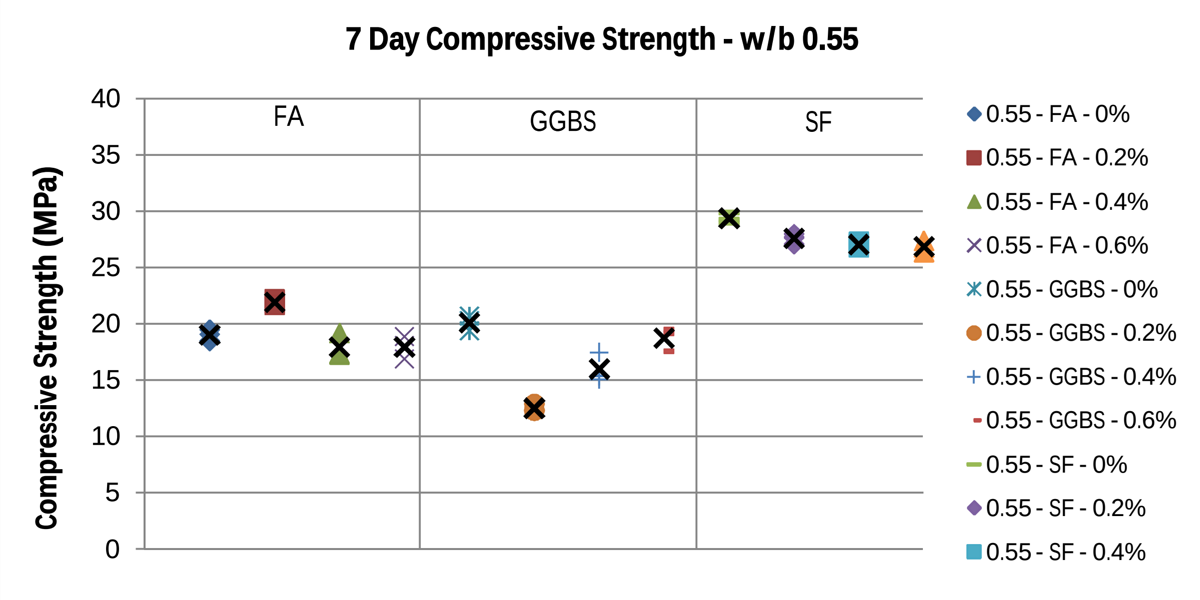

Figure 4-4: 7 day compressive strength results of initial mixes with a w/b of 0.55

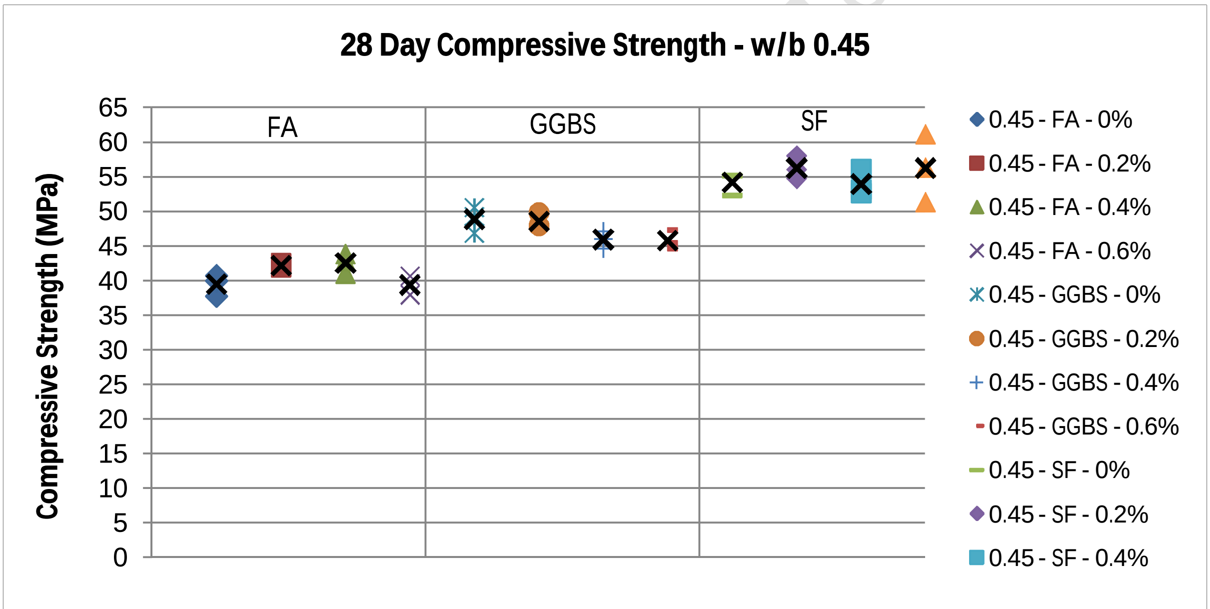

Figure 4-5: 28 day compressive strength results of initial mixes with a w/b of 0.45

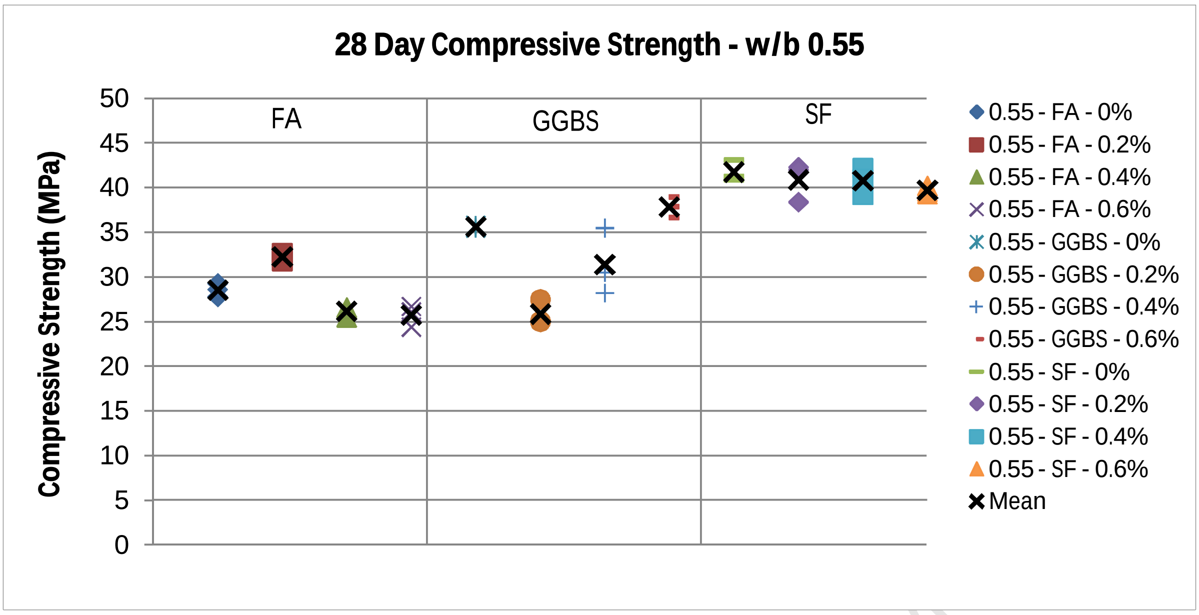

Figure 4-6: 28 day compressive strength results of initial mixes with a w/b of 0.55

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4.1.1.1 Fly Ash (FA) compressive strength results

The results of the compressive strength test on FA samples with a w/b ratio 0.45 are similar regardless of SAP content. This is true for all sample ages. The porosity results of this sample, shown in Chapter 4.1.3.4, are also similar regardless of SAP quantity. Porosity is an important characteristic in determining compressive strength. Literature suggests that an increase in void content results in a decrease in compressive strength, while a decrease in void content results in an increase in compressive strength. As the quantity of SAP added did not influence compressive strength or porosity, it suggests that the addition of SAP's do not influence the compressive strength of these FA samples.

The results of the compressive strength test on FA samples with a w/b ratio 0.55 suggest that compressive strength increased for samples with a SAP content of 0.2%, but then decreased with a further increase in SAP content. This is true for samples tested at 3, 7 and 28 days. The porosity results, shown in Chapter 4.1.3.4, show an increasing porosity with an increasing SAP content. As literature suggests, an increase in void content results in a decrease in compressive strength. This could explain why samples with a higher SAP content showed a decrease in compressive strength.

4.1.1.2 Ground Granulated Blastfurnace Slag (GGBS) compressive strength results

The results of the compressive strength test on GGBS samples with a w/b ratio 0.45 suggest that an increased SAP content results in a decrease in compressive strength. This is true for samples tested at 3, 7 and 28 days. The porosity results, shown in Chapter 4.1.3.4, show an increasing porosity with an increasing SAP content. The results correspond well with the literature, which suggests that an increase in void content results in a decrease in compressive strength.

The results of the compressive strength test on GGBS samples with a w/b ratio 0.55 do not show any clear trends. All samples containing SAP's have a lower compressive strength than the control samples. This is true for all test ages. This suggests that the addition of GGBS decreases concrete compressive strength for samples with a w/b ratio of 0.55.

4.1.1.3 Silica Fume (SF) compressive strength results

The results of the compressive strength test on SF samples with a w/b ratio 0.45 suggest that an increase in SAP content results in a very slight increase in compressive strength. This is true for all sample ages. This correlates well with the porosity results, shown in Chapter 4.1.3.4, which show a decrease in porosity with an increase in SAP content, hence increasing compressive strength.

The results of the compressive strength test on SF samples with a w/b ratio 0.55 suggest that an increasing SAP content results in a decrease in compressive strength at early ages. However, the compressive strength results at 28 days are all similar. This suggests that the addition of SAP's do not improve compressive strength at early ages, but may increase compressive strength at later ages due to water being available for the hydration reaction for a longer period of time due to the internal water source.

4.1.1.4 Comparison of compressive strength for different cement extenders

The results of the 3, 7 and 28 day compressive strength tests indicate that the mixes containing SF have a higher compressive strength than the other test specimens containing FA and GGBS. This is true for both the 0.45 and 0.55 w/b ratios considered. These results were to be expected as literature suggests that the addition of SF into a concrete mix increases the matrix density and thus increases the compressive strength.

There was no significant difference between the results of the FA and GGBS mixes, with the FA mixes having slightly higher compressive strength values when compared to the GGBS mixes for both the w/b ratios considered at 3 and 7 days of age. After 28 days, the GGBS mixes had a slightly higher compressive strength than the FA mixes. This could be due to mixes containing FA having slower strength gain than other extenders.

The compressive strength of both FA and GGBS were all lower than the SF results. As compressive strength is an important characteristic when considering concrete repair mortars, the SF mixes performed optimally. Further testing on the SF mixes is suggested.

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4.1.2 Tensile Strength Results

Due to the large number of samples to be tested, time constraints and the availability of only one UTM, the tensile strength results were obtained from the average of only two dogbone samples tested. Test ages considered for the tensile strength tests were 3 and 14 days. Samples tested at 3 days would provide data on early age tensile strength, while samples tested at 14 days would be used to assess tensile strength at later ages. Good tensile strength at early ages is an important characteristic for concrete overlays. The results of the tensile strength tests can be seen in Figures 4.7 – 4.10.

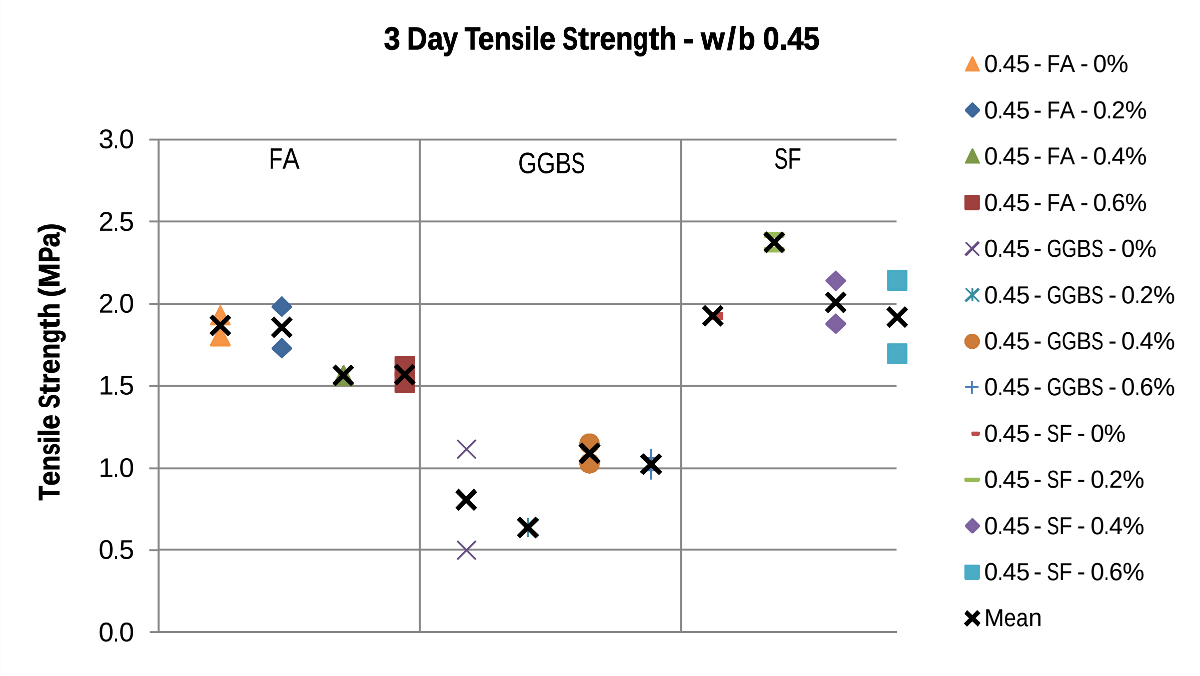

Figure 4-7: 3 day tensile strength results of initial mixes with a w/b of 0.45

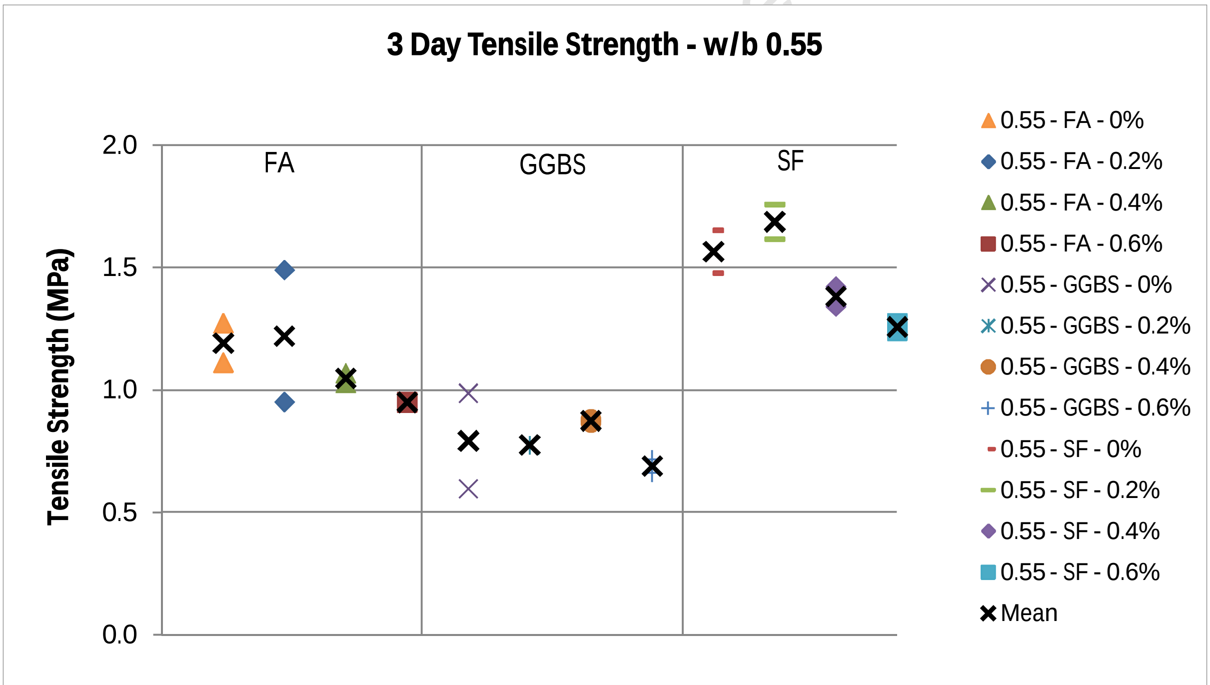

Figure 4-8: 3 day tensile strength results of initial mixes with a w/b of 0.55

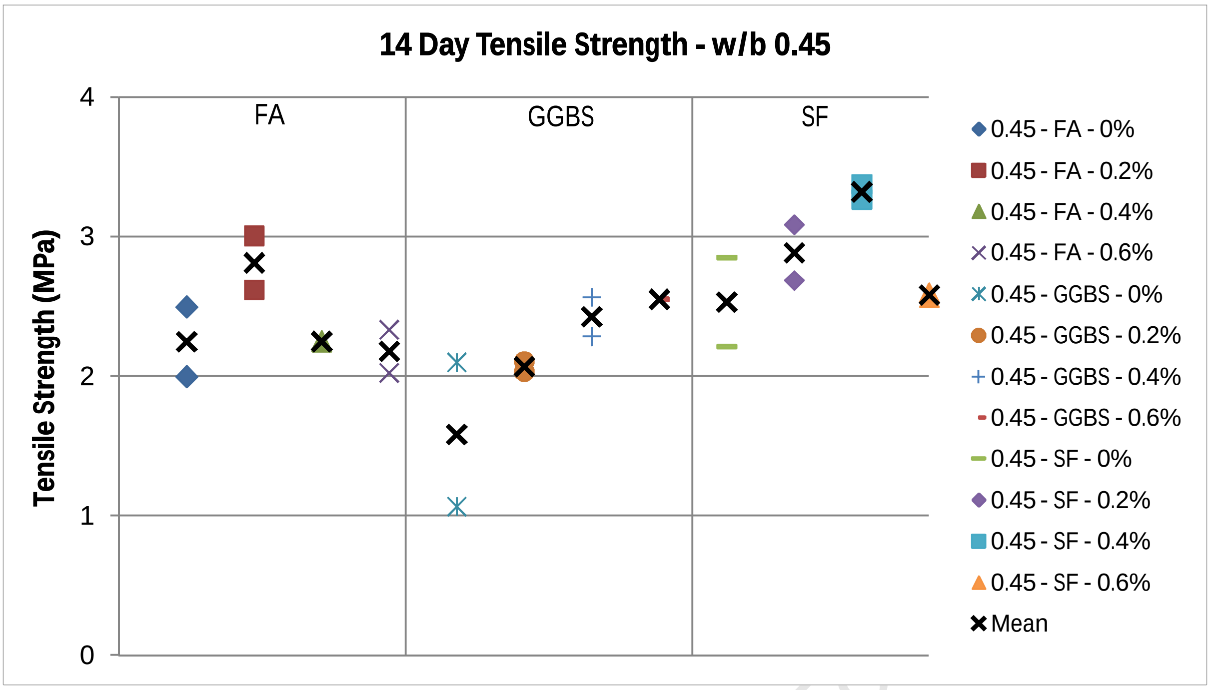

Figure 4-9: 14 day tensile strength results of initial mixes with a w/b of 0.45

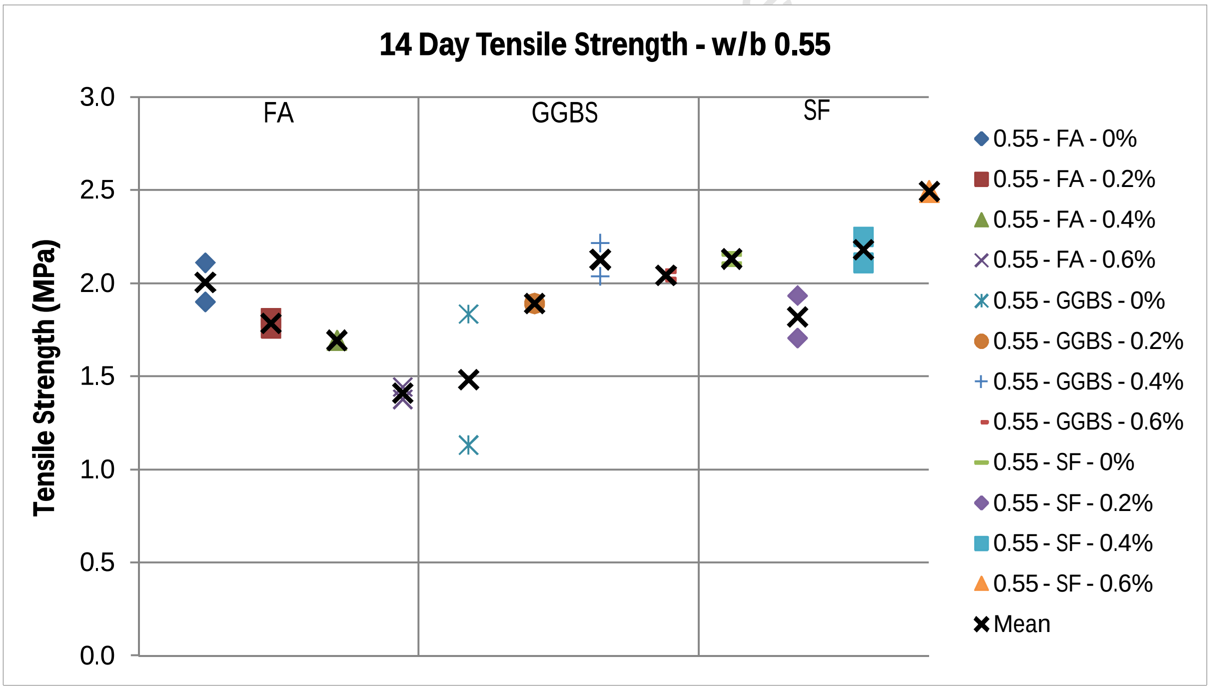

Figure 4-10: 14 day tensile strength results of initial mixes with a w/b of 0.55

4.1.2.1 FA tensile strength results

The results of the tensile strength test on FA samples with a w/b ratio 0.45 suggest that an increase in the quantity of SAP added decreases tensile strength. This is true for both sample ages tested. This trend is also true for samples with a w/b of 0.55. This suggests that the addition of SAP's has a detrimental effect on FA mixes.

4.1.2.2 GGBS tensile strength results

The results of the tensile strength test on GGBS samples tested at 3 days do not show any clear trends for both w/b ratios tested. There is a large scatter for the control samples tested for both w/b ratios. Additional samples would need to be tested in order to determine the tensile strength of the control samples.

However, samples tested at 14 days of age show that the addition of SAP's increased the tensile strength of the GGBS. This is true for both w/b ratios considered. Literature suggests that due to more water being available, due to the entrained water within the SAP's, hydration will continue for a longer period, producing more CSH, hence an increase in tensile strength.

4.1.2.3 SF tensile strength results

The results of the tensile strength test on samples containing SF show contrasting results for different sample ages. The results of the 3 days tensile strength test indicate that an increase in SAP content results in a decrease in tensile strength. However, samples tested at 14 days show the opposite, with tensile strength increasing with an increase in SAP content. This above trend is visible for both w/b ratios tested. Due to only two samples being tested per mix, this author suggests that additional samples be tested in order to determine the effect of SAP's on the tensile strength of samples containing SF.

4.1.2.4 Comparison of tensile strength for different cement extenders

At an age of 3 days, the SF mixes had larger tensile strength values than the FA and GGBS mixes. This was true for both the 0.45 and 0.55 w/b ratios. This is significant as good early age tensile strength plays a large role in crack prevention. This suggests that the SF mixes develop good tensile strength at early ages and will be able to resist any tensile stresses that develop within the overlay.

At an age of 14 days, the recorded values are all closer, but the SF mixes still outperform their equivalent FA and GGBS mixes. The results of the FA and GGBS mixes are again similar, but still lower than the SF mixes. The larger 3 day strength of the SF mixes indicate that they may have the potential to resist early-age cracking and further testing on this mix is suggested. More samples and testing ages should be considered in order to monitor tensile strength development of the SF mixes, as well as determine the influence of SAP's on tensile strength for these mixes.

4.1.3 Durability

The durability characteristics of repair mortars are important in determining their functionality. Good durability will ensure that aggressive agents, such as chlorides and carbon dioxide, do not reach the steel reinforcing causing the steel to corrode. If a repair mortar does not meet the durability requirements, the repair will fail regardless of the tensile, compressive or bond strength of the mix. The durability of the repair mortars were evaluated according to the UCT Durability Index tests discussed in Chapter 3.2.5.3.

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4.1.3.1 Oxygen Permeability Index (OPI) Results

The OPI tests were conducted according to the UCT Durability Index test standards. The method followed is discussed in Chapter 3.2.5.3. The results are shown in Figures 4.11 and 4.12.

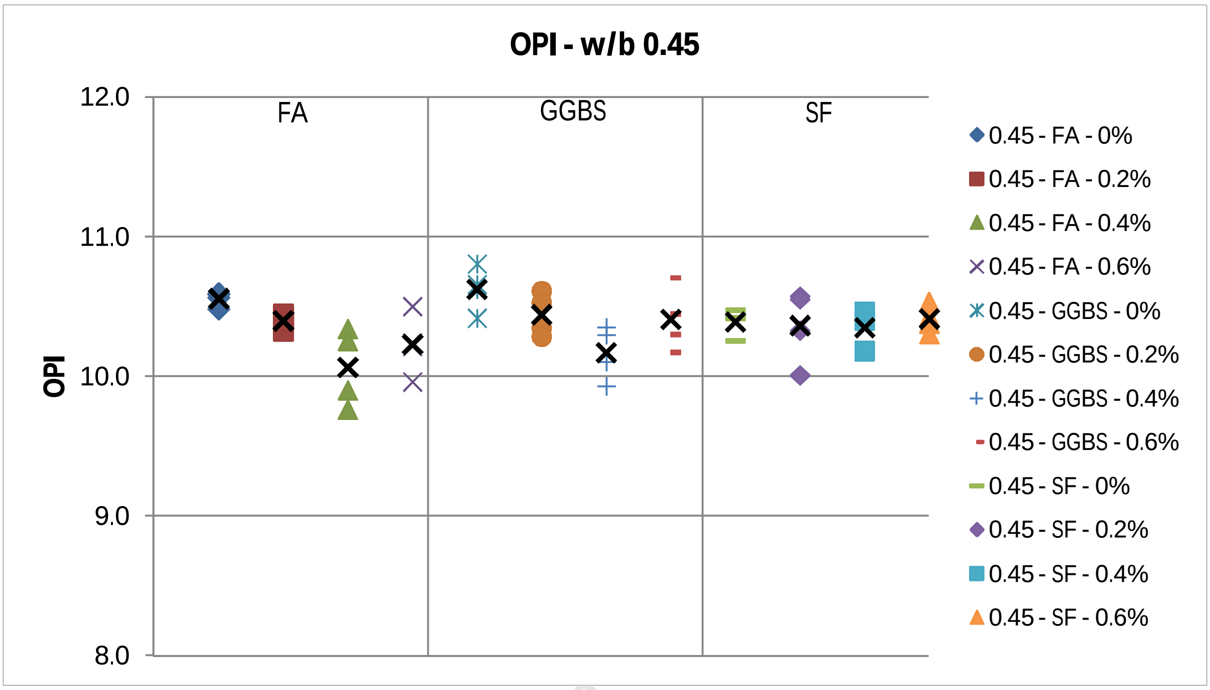

Figure 4-11: OPI results of the initial mixes with a w/b of 0.45

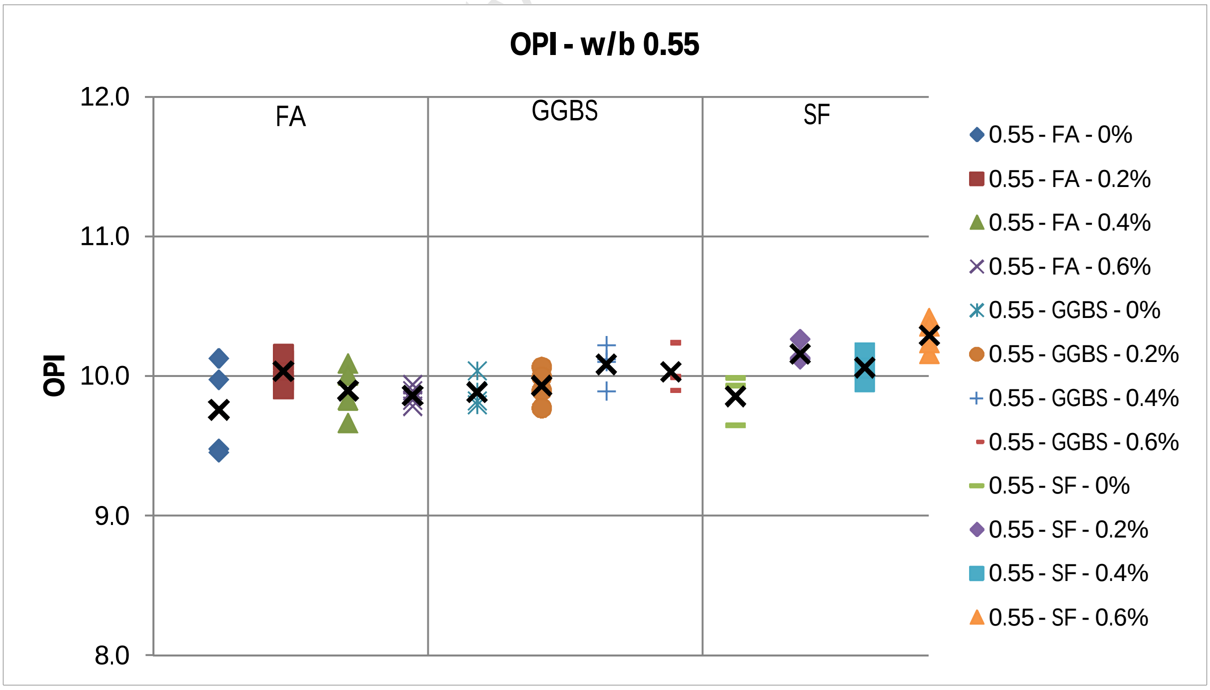

Figure 4-12: OPI results of the initial mixes with a w/b of 0.55

The results of the OPI testing on the FA and GGBS mixes with a w/b of 0.45 show that an increase in SAP content results in a decrease in OPI. The addition of SAP's has no influence on the OPI results of the SF mix with a w/b ratio of 0.45. The results of all testing on the mixes with a w/b of 0.45 are all similar for the equivalent SAP content and are all above 10, representing excellent durability.

The results of the OPI testing on the FA, GGBS and SF mixes with a w/b of 0.55 show that an increase in SAP content results in a small increase in OPI. The OPI results for the FA and GGBS mixes were all just below 10, representing good durability. The OPI results for the SF mixes were all above 10, representing excellent durability.

The results of the testing of the 0.45 w/b samples suggest that all samples perform similarly. However, the OPI result of the SF mix with a w/b ratio of 0.55 was higher than the other 0.55 w/b ratio samples, suggesting that the SF mixes performed best.

4.1.3.2 Chloride Conductivity (CC) Results

The Chloride Conductivity tests were conducted according to the UCT Durability Index test standards. The method followed is discussed in Chapter 3.2.5.3. The results are shown in Figures 4.13 and 4.14.

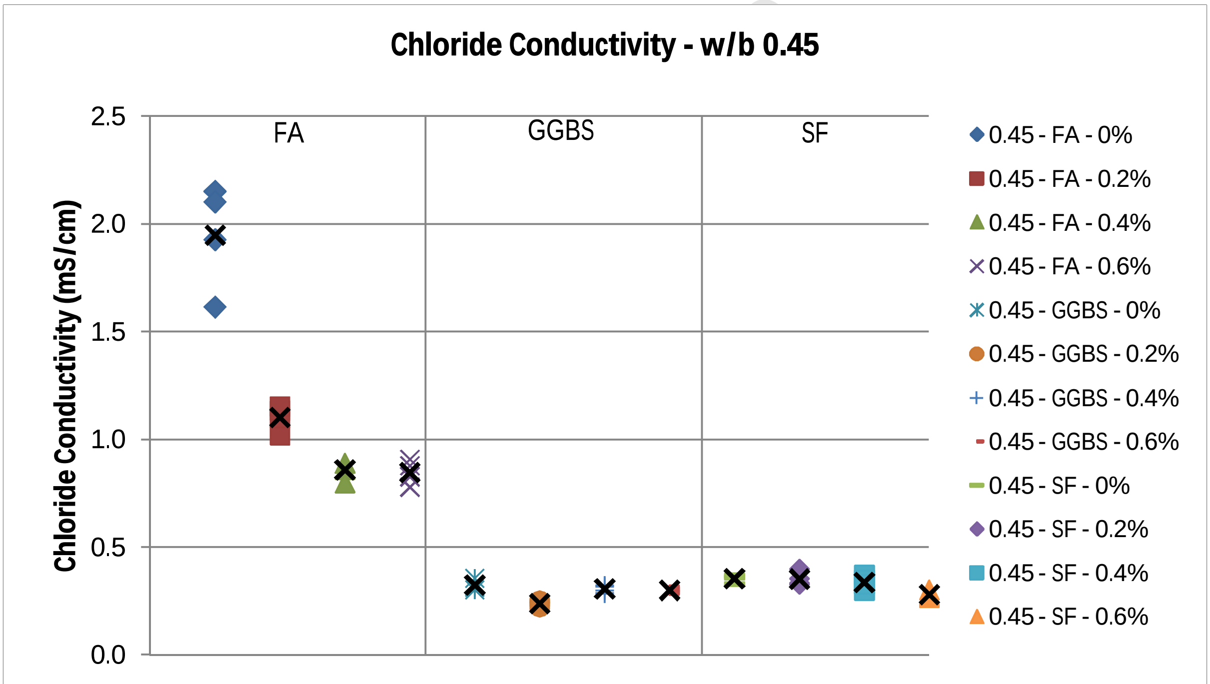

Figure 4-13: Chloride Conductivity results of the initial mixes with a w/b of 0.45

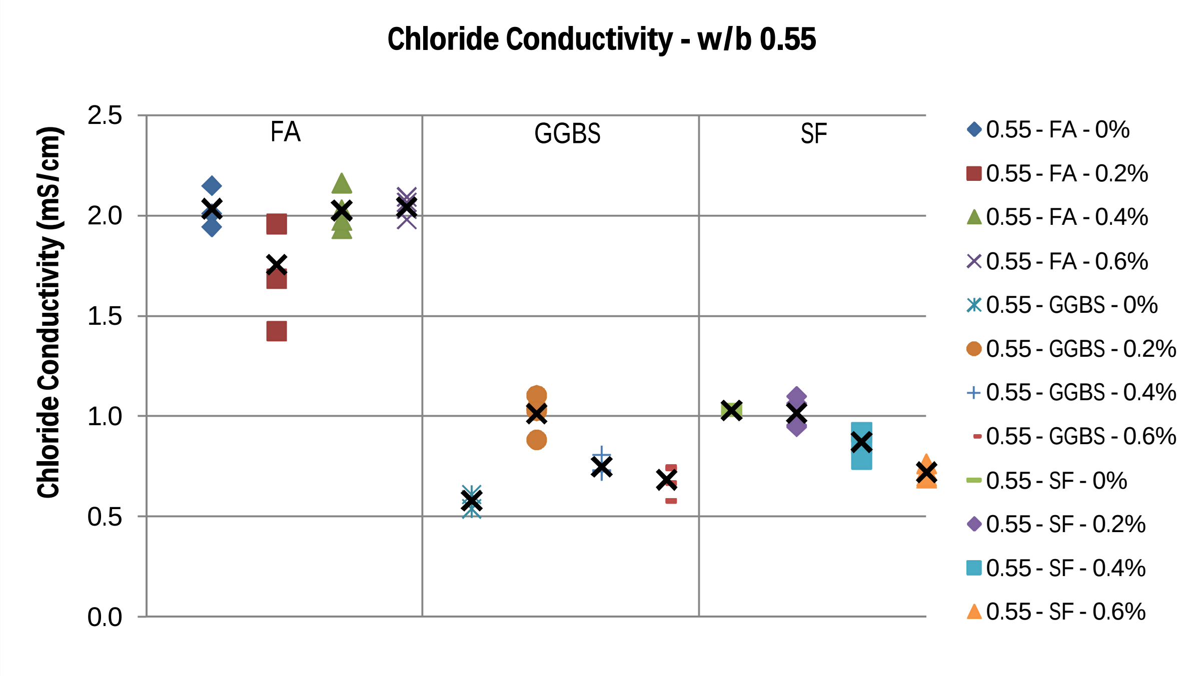

Figure 4-14: Chloride Conductivity results of the initial mixes with a w/b of 0.55

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The CC results of the tests conducted on the FA mix with a w/b of 0.45 indicate that the increase in the quantity of SAP reduced the recorded CC value, indicating an improvement in chloride resistance with an increase in SAP content. The recorded values for the FA mixes indicate good chloride resistance. The results for the mixes containing GGBS and SF with a w/b ratio of 0.45 suggest that an increase in SAP content results in a small decrease in CC, suggesting an improvement in chloride resistance with an increase in SAP content. The results of the GGBS and SF testing are below 0.5 mS/cm, indicating excellent chloride resistance.

The results of the CC testing on FA mixes with a w/b ratio 0.55 show a slight decrease in CC with an increase in SAP content. However, the CC values lie between 1.75 and 2.55 mS/cm, which are an indication of poor durability, thus they do not meet the durability requirements of this research. The results of the CC testing on GGBS mixes with a w/b of 0.55 show that all samples containing SAP's have a higher CC value than the control sample. This suggests that the addition of SAP's adversely affects chloride resistance of the GGBS samples. The results of the CC testing on the SF mixes with a w/b ratio of 0.55 show that an increase in SAP content results in a decrease in CC value, hence better durability.

4.1.3.3 Sorptivity Test Results

The Sorptivity tests were conducted on the same samples used for the OPI tests, as per the UCT Durability Index test standards. The method followed is discussed in Chapter 3.2.5.3. The results are shown in Figures 4.15 and 4.16.

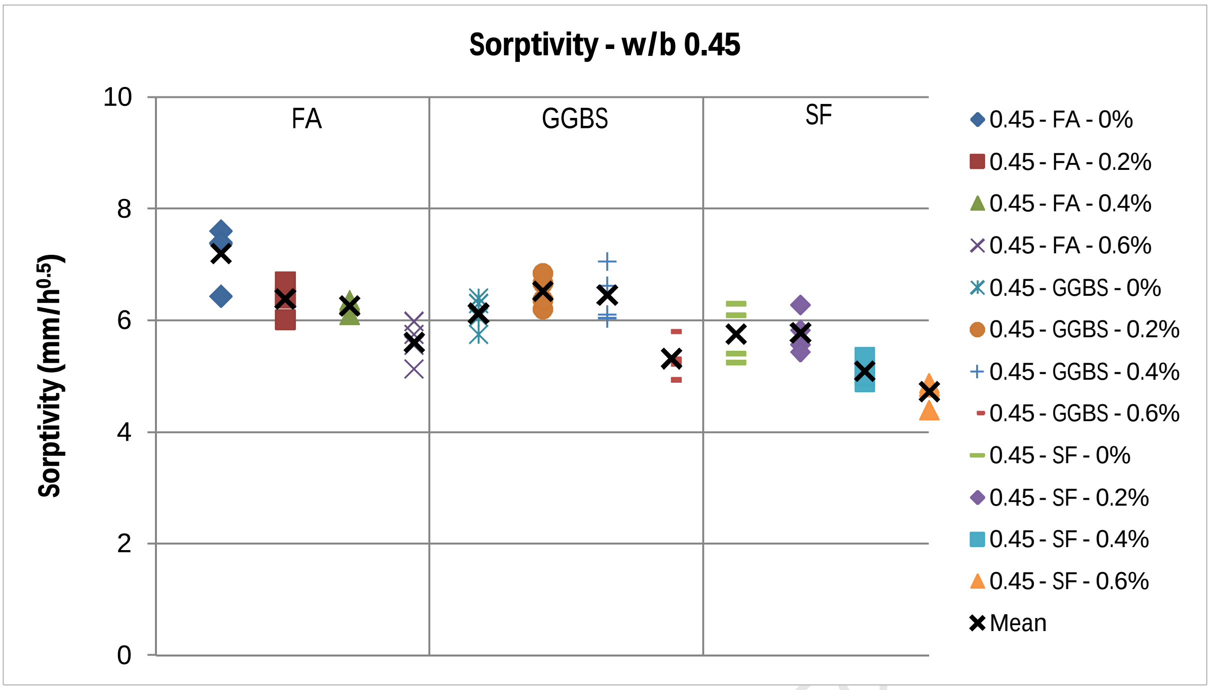

Figure 4-15: Sorptivity results of the initial mixes with a w/b of 0.45

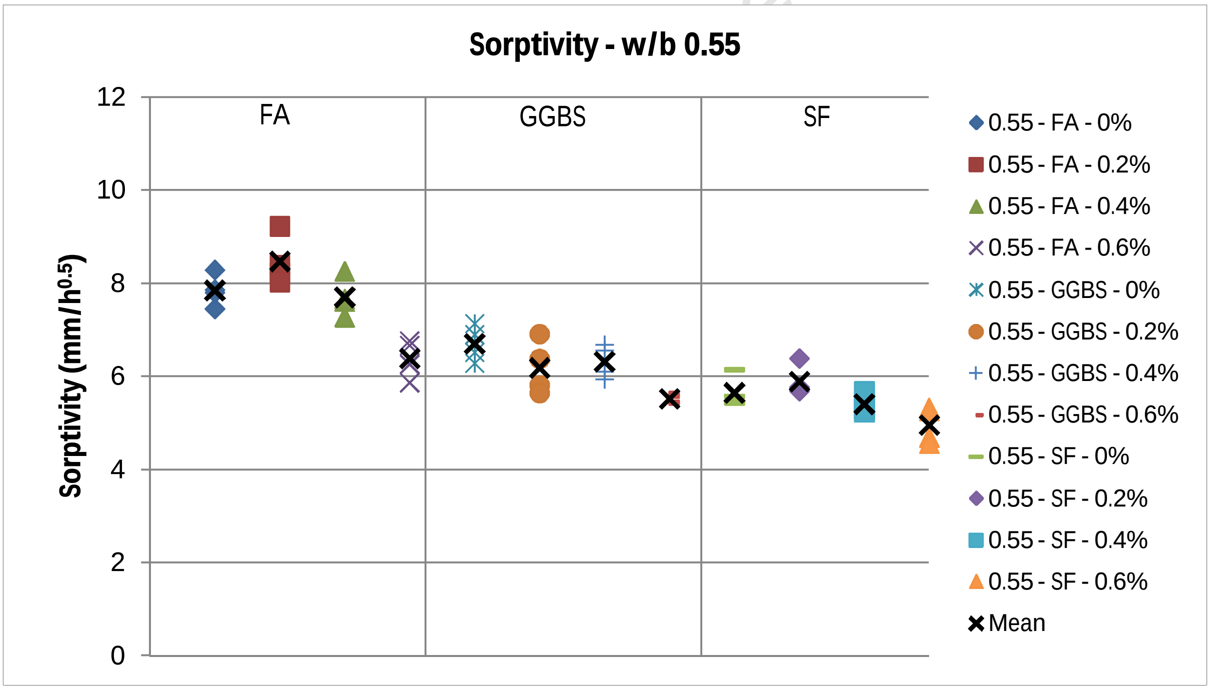

Figure 4-16: Sorptivity results of the initial mixes with a w/b of 0.55

The results of the sorptivity testing on the FA and SF mixes with a w/b ratio of 0.45 show that an increase in SAP content results in a decrease in sorptivity. The results of the GGBS with a w/b ratio of 0.45 testing show the opposite, with an increase in SAP content resulting in an increase in sorptivity.

The results of the sorptivity testing on the FA, GGBS and SF mixes with a w/b ratio of 0.55 show that an increase in SAP content results in a decrease in sorptivity.

4.1.3.4 Porosity Results

The porosity of the samples was calculated during the sorptivity testing, as per the UCT Durability Index test standards. The results are shown in Figures 4.17 and 4.18.

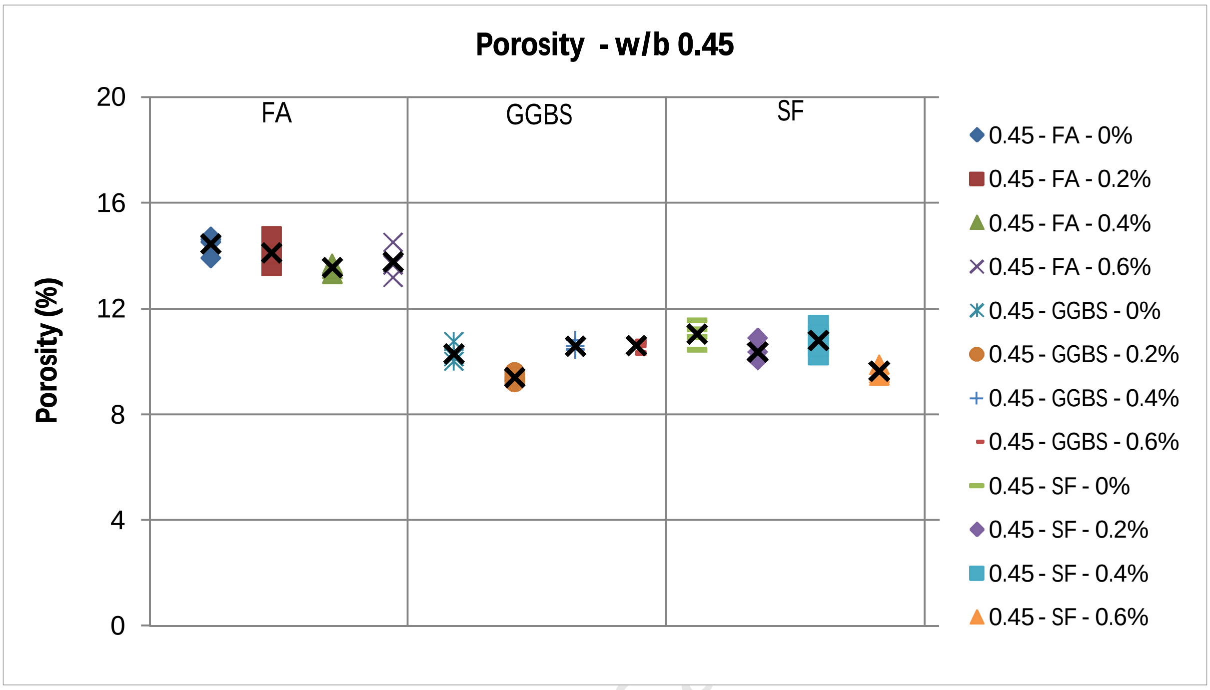

Figure 4-17: Porosity results of w/b 0.45 mixes calculated from sorptivity testing

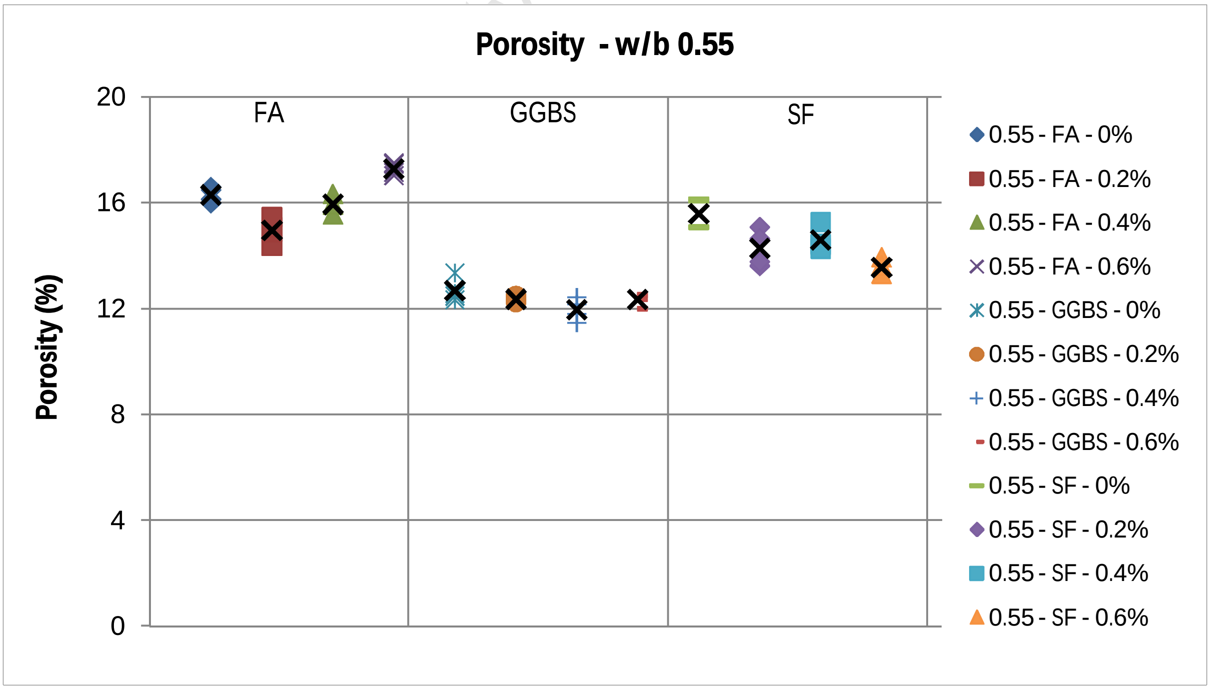

Figure 4-18: Porosity results of w/b 0.55 mixes calculated from sorptivity testing

The results of the porosity testing on the FA mixes with a w/b ratio of 0.45 show that an increase in SAP content results in a small decrease in porosity. However, no clear trend can be seen regarding the influence on SAP content on FA samples with a w/b ratio of 0.55.

The results of the porosity testing on the GGBS showed that the quantity of SAP added did not influence the porosity results as all samples had similar porosities. This is true for both w/b ratios tested.

The results of the porosity testing of the SF mixes suggest that an increase in SAP content results in a decrease in porosity. This is true for both w/b ratios considered in this research. This suggests that the addition of SAP positively influences the porosity of samples containing SF.

4.1.4 Comparison of Initial Mixes Tested

The addition of SAP's as a method of internal curing affected the characteristics of the different cement extenders differently. A brief summary of the influence of SAP's on each extender is discussed below.

4.1.4.1 Influence of SAP's on FA mixes

The addition of SAP's had a negative impact on the compressive strength results of the FA mixes for both w/b ratios tested. An increase in SAP content resulted in a decrease in compressive strength at all ages tested. The above trend was also true for tensile strength, with an increase in SAP content resulting in a decrease in tensile strength for both w/b ratios tested.

The addition of SAP's adversely affected the OPI results for samples with a w/b ratio of 0.45, but improved chloride conductivity and sorptivity results and porosity results. The addition of SAP's did not impact on the OPI results of the mixes with a w/b ratio of 0.55. An increase in SAP content resulted in a decrease in CC for samples with a w/b ratio of 0.45, but did not impact on the CC results of samples with a w/b ratio 0.55.

4.1.4.2 Influence of SAP's on GGBS mixes

The addition of SAP's had a negative effect on the compressive strength of the GGBS mixes for both w/b ratios at all 3 sample ages. The increase in SAP content resulted in a decrease in compressive strength. The tensile strength results showed the positive affect of SAP's with an increasing SAP content resulting in increasing tensile strength. This was observed for both w/b ratios considered.

The OPI and sorptivity results of the mixes with a w/b ratio of 0.45 were negatively affected by the addition of SAP's, while the CC and porosity results were unaffected by the addition of SAP's.

The OPI and sorptivity results of the mixes with a w/b ratio of 0.55 were improved by the addition of SAP's, while the CC results were negatively affected by the addition of SAP's. The porosity results were unaffected by the addition of SAP's.

4.1.4.3 Influence of SAP's on SF mixes

The compressive strength of samples with a w/b ratio of 0.45 were unaffected by the addition of SAP's with all mixes having similar compressive strengths regardless of SAP content for all sample

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ages considered. The addition of SAP's had a small negative impact on the samples with a w/b ratio 0.55 with an increase in SAP content resulting in a small decrease in compressive strength. This is true for all sample ages tested.

The results of the of the tensile strength testing suggest that an increasing SAP' content has a negative impact on compressive strength at early ages, but a positive effect at later ages. This is true for both w/b ratios considered.

The addition of SAP's had no impact on OPI results of samples with a w/b ratio of 0.45, while an increasing SAP content increased OPI results for samples with a w/b ratio of 0.55. An increase in SAP content resulted in improvement in CC, sorptivity and porosity results for both w/b ratios tested.

4.1.4.4 Summary of Initial Test Results

The purpose of the initial testing was to determine which mixes performed optimally in terms of three important overlay requirements; compressive strength, tensile strength and durability. Due to a lack of available research, the impact that SAP's would have on the three cement extenders used in this research was unknown. The initial mixes were assessed based on the results of the initial testing.

The results of the compressive strength testing showed that an increase in SAP content would result in a decrease in compressive strength. However, the samples containing SF were least negatively affected by the addition of SAP's. In addition, the SF mixes containing SF had the highest compressive strength values when compared to the other mixes tested.

Generally, tensile strength of the samples increased with an increasing SAP content for all samples at later ages. However, the SF mixes had the largest tensile strength when compared to the other samples tested at both sample ages considered. Tensile strength is an important property for overlays and with that in mind, the SF mixes out-performed the other test mixes.

In terms of durability, all samples with a w/b ratio performed similarly in terms of OPI. The SF mixes performed the best in terms of OPI for the samples with a w/b ratio of 0.55 with an increase in SAP content resulting in an increase in OPI. Generally, an increase in SAP content reduced the CC values for both w/b ratios. The SF mixes had the lowest CC values for sampled with a w/b ratio of 0.45, while the GGBS mixes had the lowest CC values out of the samples tested with a w/b ratio of 0.55. The SF mixes had the lowest sorptivity values for both w/b ratios tested, with an increase in SAP content decreasing sorptivity for both w/b ratios considered.

Based on the above assessment, the SF mixes outperformed the other test mixes based on the initial testing. For this reason, it is proposed that the SF mixes be subjected to further testing relating to other important bonded concrete overlay characteristics.

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4.2 Results of Further Testing of SF Mixes

The results of the initial testing showed that the SF mixes met the performance criteria of this research. To further confirm the initial tests results, the initial tests were repeated for the SF mixes. Additional testing conducted included free shrinkage, restrained shrinkage, shear bond strength, tensile relaxation, elastic modulus, carbonation testing, bulk diffusion testing and transmitted, reflected light and scanning electron microscopy. The results of these tests are shown and discussed below.

4.2.1 Compressive Strength Results

The results of the compressive strength testing can be seen in Figure 4.19.

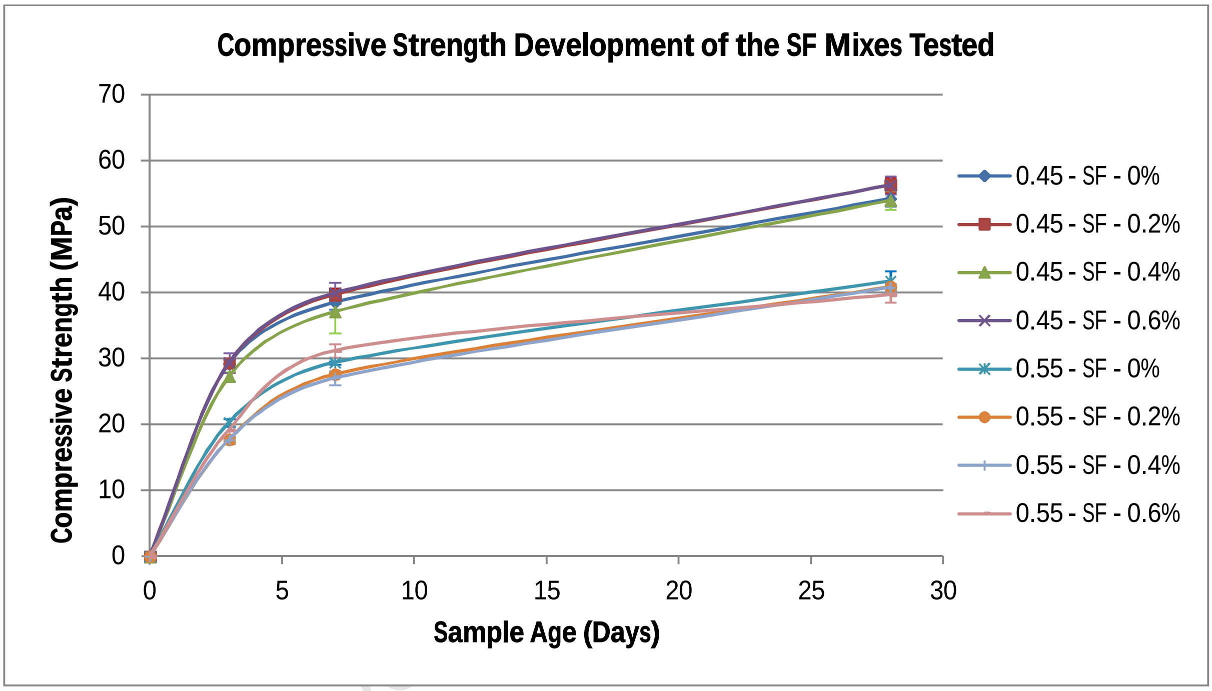

Figure 4-19: Graphical representation of compressive strength test results

The results of the initial compressive strength testing were used to analyse the influence of SAP content on compressive strength. The results were discussed briefly in Chapter 4.1.1.3.

Porosity plays an important part in determining compressive strength. Kolver & Jensen (2007) suggest that a 1% increase in voids results in a 5% decrease in compressive strength. The porosity result, shown in Figure 4.26 and discussed in Chapter 4.2.3.3 suggest that the addition of SAP's changes the microstructure of the concrete overlay by reducing the quantity of fine capillary voids, while increasing the quantity of larger macro pores. The increase in the quantity of macro pores could potentially decrease compressive strength.

Each w/b ratio had similar compressive strength values at the same ages, regardless of SAP content. A possible reason for this similar strength is that the SAP particles hold any additional free mix water within their structure, which will then be available for the hydration reaction whenever necessary. This would result in an increase in the products of hydration as the reaction will occur over a longer period of time. This increase in hydration products will counteract any negative effects relating to the increased quantity of macro pores. This suggests that the use of SAP's can be incorporated into concrete mix design without decreasing the expected compressive strength.

4.2.2 Tensile Strength Results

Tensile strength tests were conducted as per the method discussed in Chapter 3.2.5.2. Additional tensile strength samples were cast and tested at ages of 3, 7 and 14 days in order to monitor the tensile strength development at early ages. The results are shown in Figures 4.20 – 4.21.

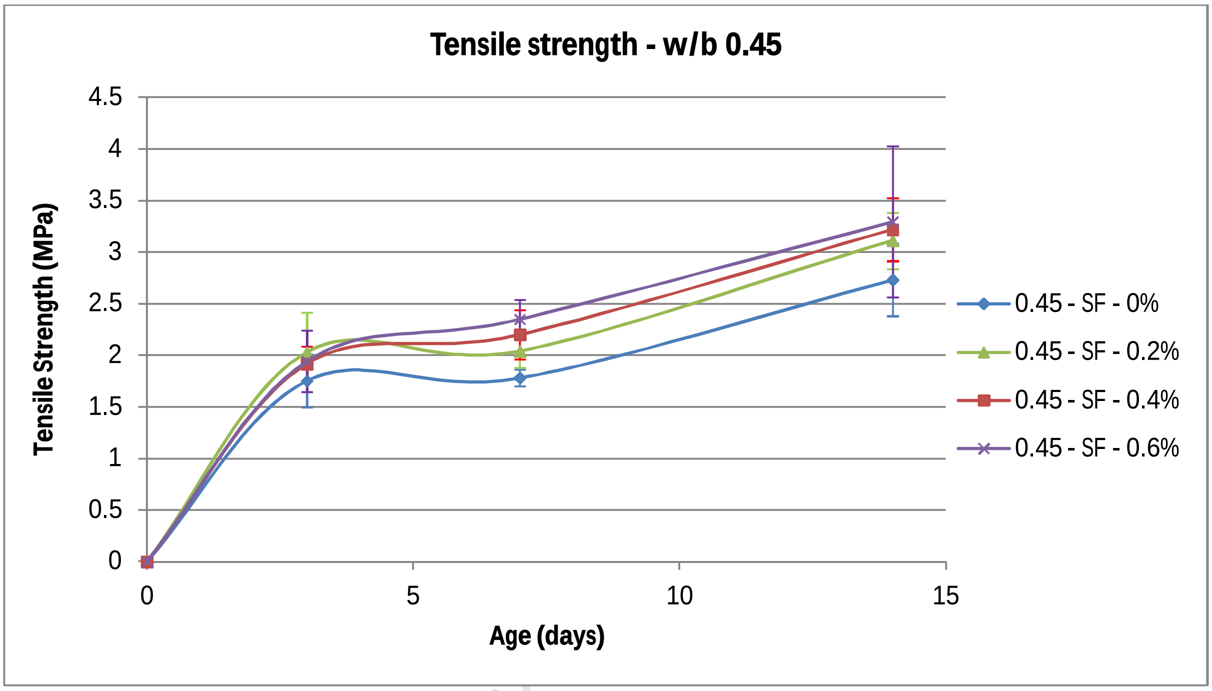

Figure 4-20: Tensile strength development of samples with w/b 0.45

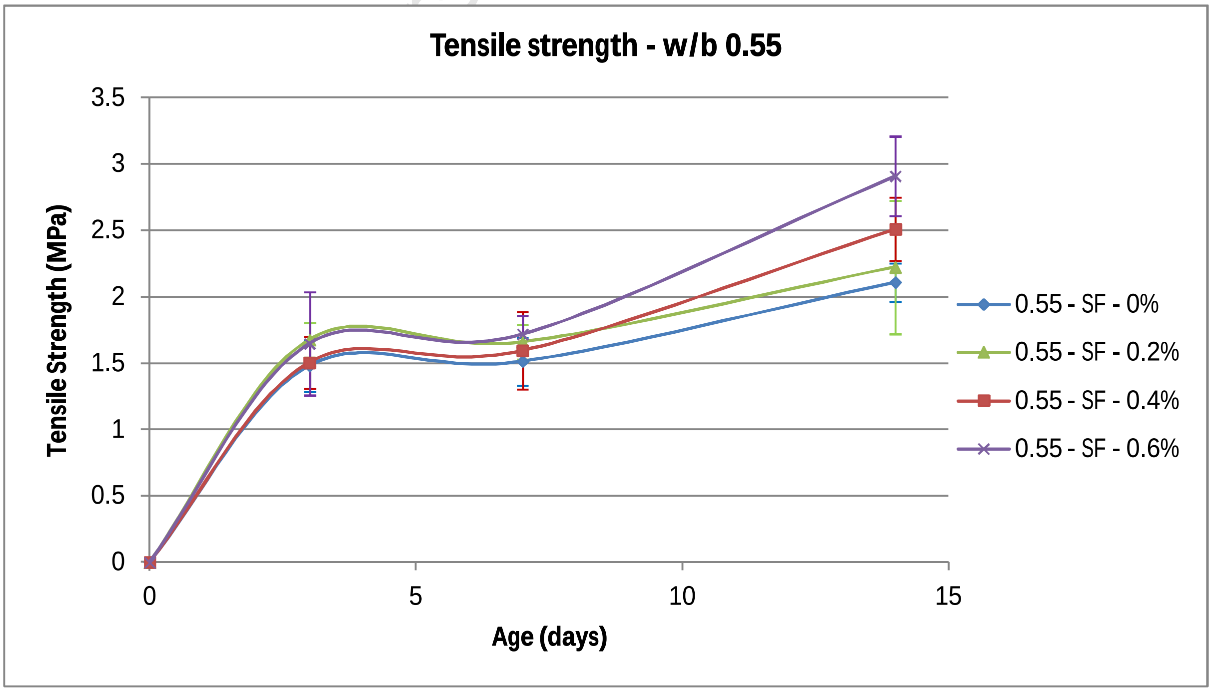

Figure 4-21: Tensile strength development of samples with w/b 0.55

Figure 4.20 and Figure 4.21 indicate that similar tensile strengths were recorded at 3 and 7 days of age. A reason for the rapid increase in tensile strength is due to the high reactivity of SF, which would speed up any strength gain at early ages. This is true for both w/b ratios tested.

The results of the tensile strength testing show that the samples containing SAP's had a higher tensile strength than the control samples. This is true for both w/b ratios tested. This could be the result of an increase in the products of hydration due to continued hydration, which would increase tensile strength development.

The results of the testing indicate that an increase in SAP content results in an increase in tensile strength. From Figure 4.26 below, it can be seen that an increase in SAP content results in a decrease in porosity. This results in a denser microstructure, which in turn could be the reason for the increase in tensile strength. This is true for both w/b ratios tested at 3, 7 and 14 days. This result is consistent with literature discussed in Chapter 2.7.3.2, as Lam (2005) found an increase in tensile splitting strength with an increase in SAP content. These results indicate that the addition of SAP's have the potential to improve the tensile strength of mortars containing SF.

4.2.3 Durability

The SF mixes were tested in terms of their resistance to carbonation and chloride ingress. Rapid and long-term tests were conducted. The rapid testing techniques used were the UCT Durability index tests. Long term testing included carbonation and bulk diffusion tests to measure carbonation depth and chloride resistance respectively. Carbonation testing involved placing samples in an exposure chamber at 4.0% CO_2 for 42 days. The full details of the test can be found in Chapter 3.2.6.6. The details of the bulk diffusion test are discussed in Chapter 3.2.6.7.

4.2.3.1 Permeability and Carbonation Results

The results of the initial OPI testing on the SF mixes, discussed in Chapter 4.1.1.3, are shown in Figure 4.22. The results of the long term carbonation ingress tests are shown in Figure 4.23.

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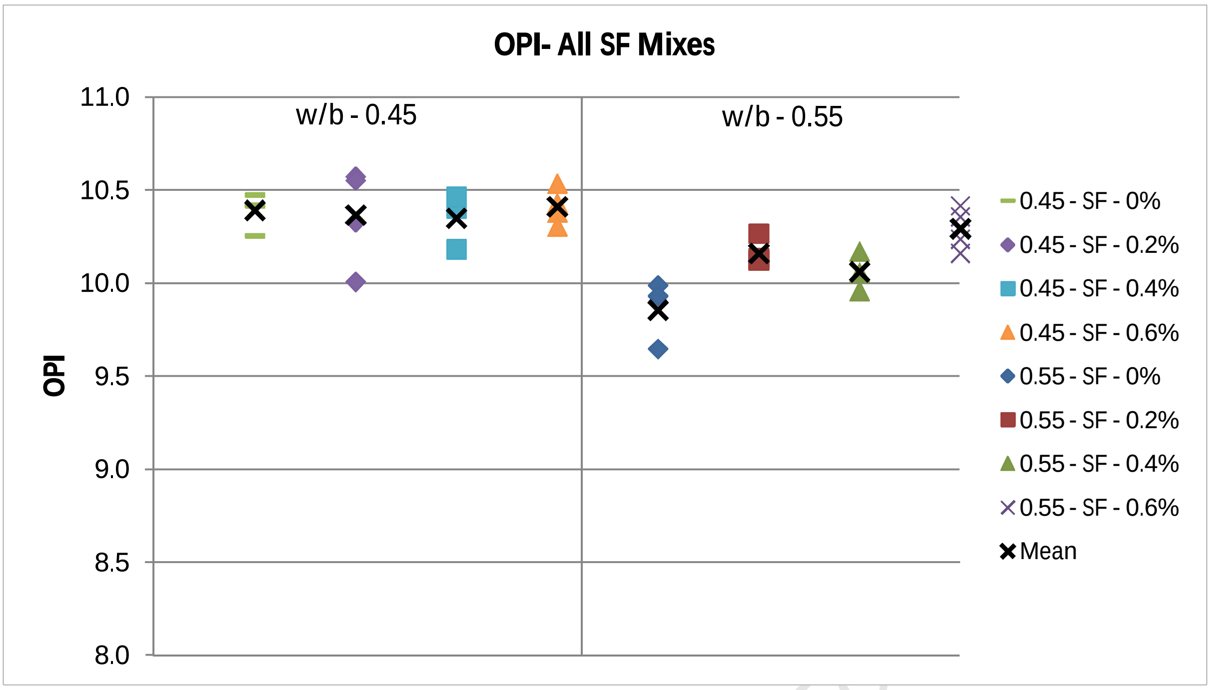

Figure 4-22: OPI results of all SF mixes tested

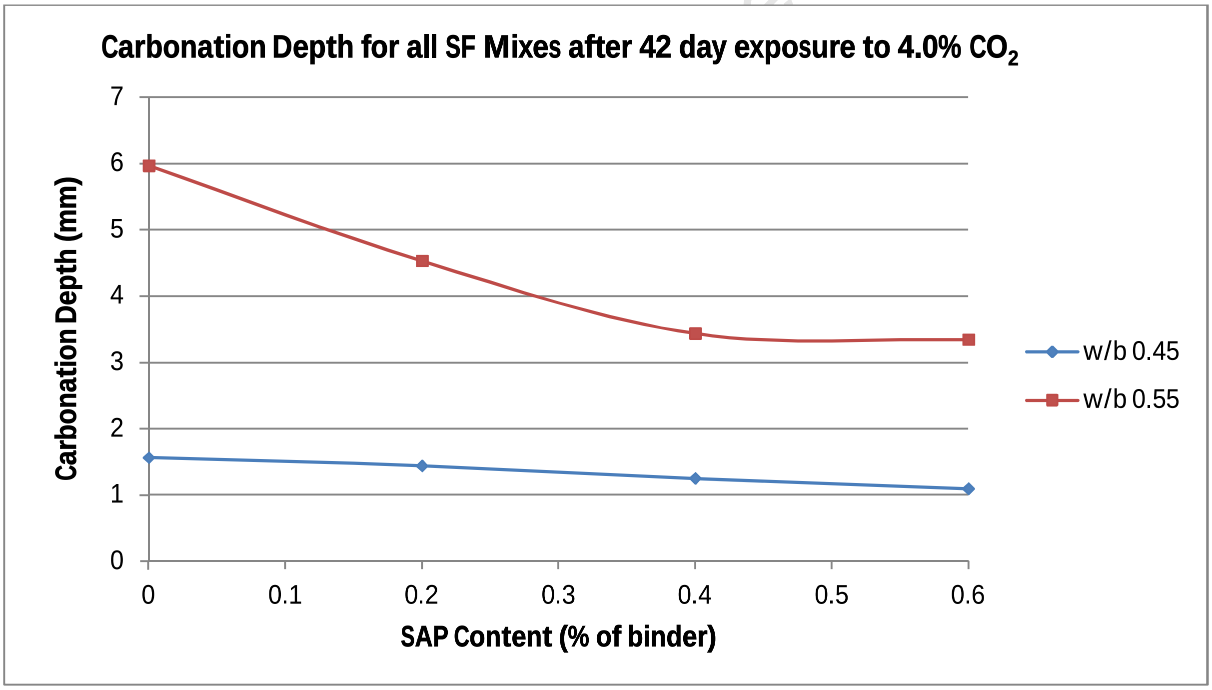

Figure 4-23: Measured carbonation depth for samples with varying SAP content

The OPI test is used to predict the ability of a concrete sample to resist carbonation ingress. The results of the OPI test in Figure 4.22 suggest that an increase in SAP content does not influence the OPI results of the mixes with w/b ratio of 0.45. The results of the carbonation testing, shown in Figure 4.23, showed similar results to the OPI testing, where an increase in SAP content resulted in a small decrease in carbonation depth.

The results of the OPI test in Figure 4.22 suggest that an increase in SAP content results in an increase in OPI value of the mixes with w/b ratio of 0.55. The results of the carbonation testing, shown in Figure 4.23, showed similar results to the OPI testing, where an increase in SAP content resulted in a decrease in carbonation depth. The improvement in OPI and carbonation depth results are more pronounced for the samples with a w/b ratio of 0.55 when compared to the samples with a w/b ratio of 0.45.

Research conducted by Jensen & Hanson (2001), discussed in Chapter 2.7.3.8, suggest that samples containing SAP's contain geometrically predesigned, regularly spaced macro pores. These macro pores replace finer, irregularly shaped, partly connected capillary pores. This reduction in connectivity of capillary pores should result in a decrease in permeability, which improved durability as it makes the ingress of aggressive agents more difficult.

All samples contained the same quantity of water initially with only the quantity of SAP changing. The size of the saturated SAP particles within the cement matrix will decrease with an increase in SAP content. This is due to less water being available to each individual SAP particle with an increase in SAP content. The reduction in pore size along with the decrease in capillary pore connectivity could explain why there is a decrease in permeability with an increase in SAP content. This will result in fewer paths being available for the ingress of aggressive agents, which improves durability.

4.2.3.2 Chloride Resistance Results

The results of the chloride conductivity and bulk diffusion test are shown in Figures 4.24 and 4.25.

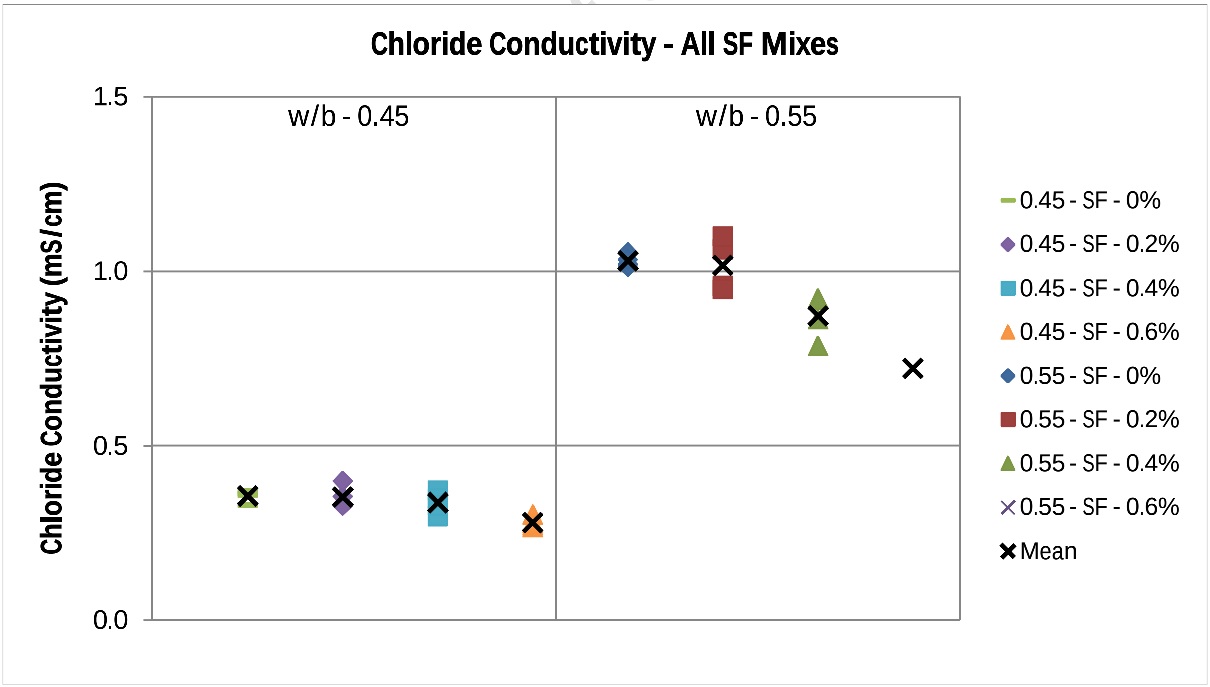

Figure 4-24: Results of the chloride conductivity testing conducted on the SF mixes

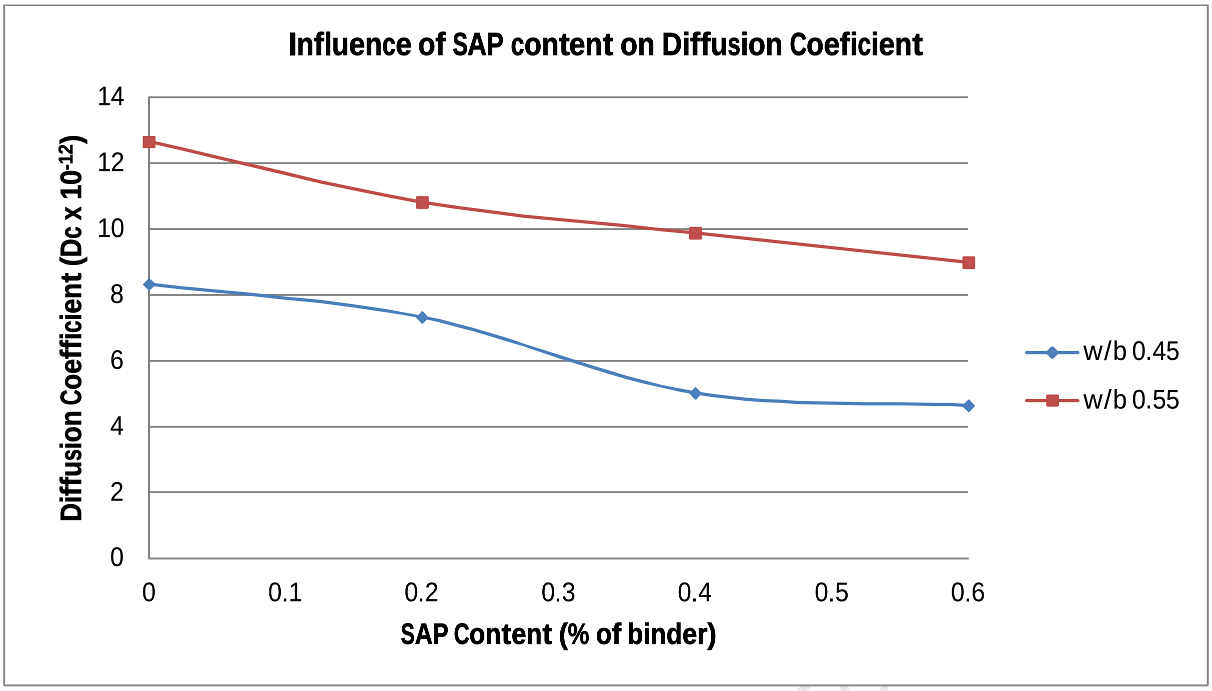

Figure 4-25: Results of the bulk diffusion tests conducted on the SF mixes

The results of the chloride conductivity test on samples with a w/b ratio of 0.45 show that there is a slight decrease in CC with an increase in SAP content. The results of the bulk diffusion test on samples with a w/b ratio of 0.45 show a more pronounced increase in chloride resistance with an increase in SAP content.

The results of the CC and bulk diffusion testing on samples with a w/b ratio of 0.55 suggest that there is increase in chloride resistance with an increase in SAP content. The influence of w/b ratio can also be seen, as the mixes with a lower w/b ratio had a larger chloride resistance.

As discussed in Chapter 4.2.3.1, an increase in SAP content will result in a decrease in capillary pore connectivity. This reduction in capillary pore connectivity should increase with an increasing SAP content. Hence an increase in SAP content will result in lower chloride ingress as there are fewer paths available for the ingress of aggressive agents. This could explain why there CC and bulk diffusion results were lower for samples containing more SAP's.

4.2.3.3 Porosity Results

The porosity for each mix was obtained from the sorptivity testing as per the UCT Durability Index test methods. The results of the porosity testing are shown in Figure 4.26.

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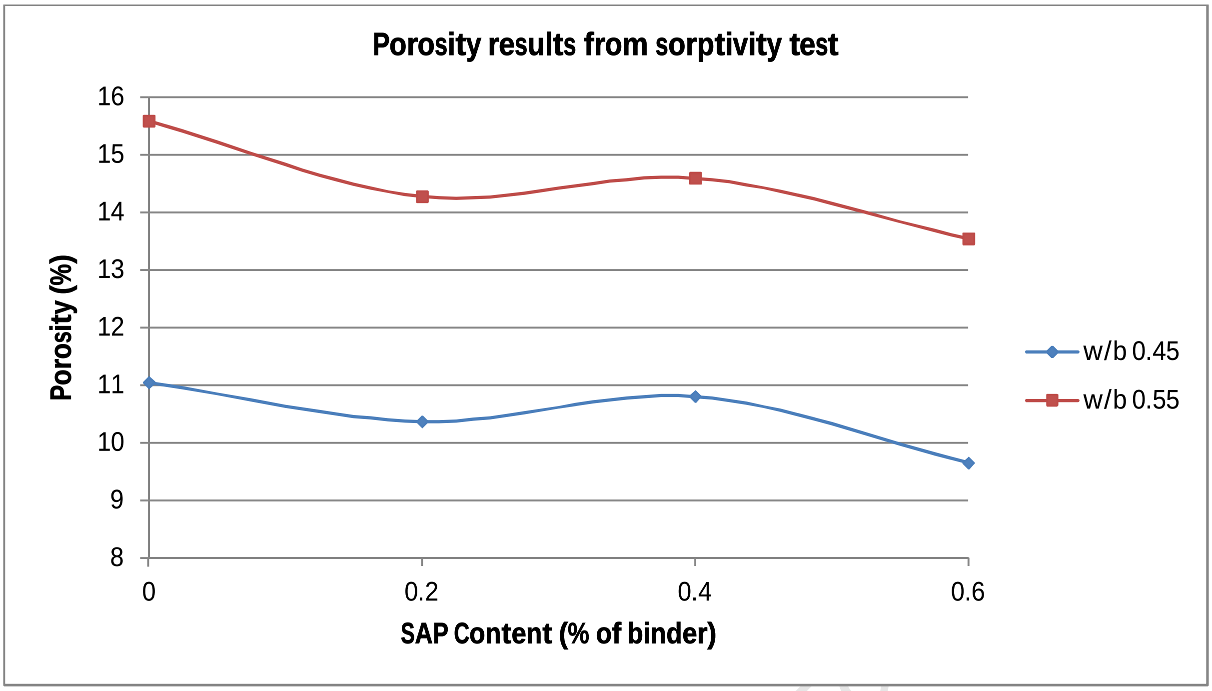

Figure 4-26: Results of the porosity testing obtained from the OPI and CC testing

The results of the porosity testing indicate that an increase in SAP content results in a decrease in porosity. This is true for both w/b ratios considered. A possible reason for could be the pore size and distribution. Research conducted by Jensen and Hanson (2001), discussed in Chapter 2.7.3.8, showed that samples containing SAP's had geometrically predesigned, regularly spaced macro pores, which replaced finer, irregularly shaped, party connected capillary pores. Literature suggests that an increase in SAP quantity will result in an increase in hydration, which will produce more CSH gel. This increase in hydration products will fill the fine capillary pores with CSH gel, hence reducing the quantity of fine voids within the cement matrix.

The addition of SAP's will result in an increase in the quantity of macro pores, while reducing the quantity of finer voids. Based on the results of the porosity testing, it suggests that the decrease in the quantity of finer capillary pores is larger than the slight increase in macro pores results in a net decrease in porosity with an increase in SAP quantity.

4.2.4 Tensile Relaxation Results

The details of the tensile relaxation testing procedure are discussed in Chapter 3.2.6.4. All samples were 3 days old at the time of testing. The results of the tensile relaxation tests conducted are shown in Figures 4.27 and 4.28.

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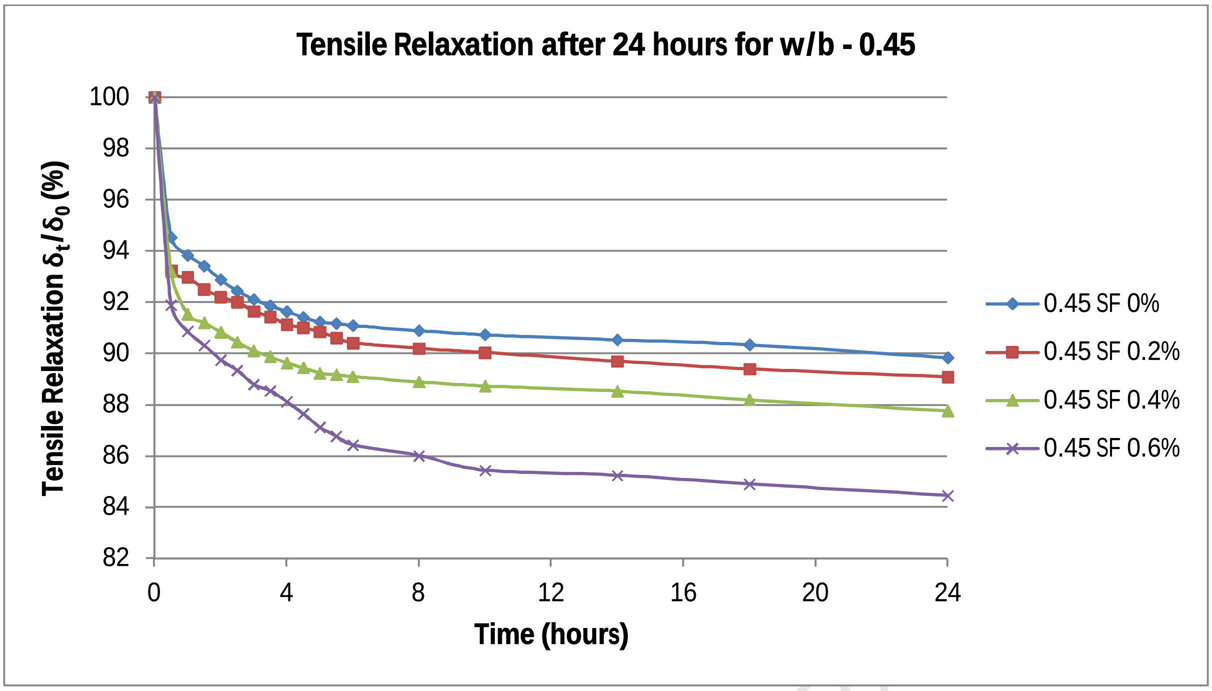

Figure 4-27: Tensile relaxation of SF samples with w/b = 0.45 over a 24 hour period

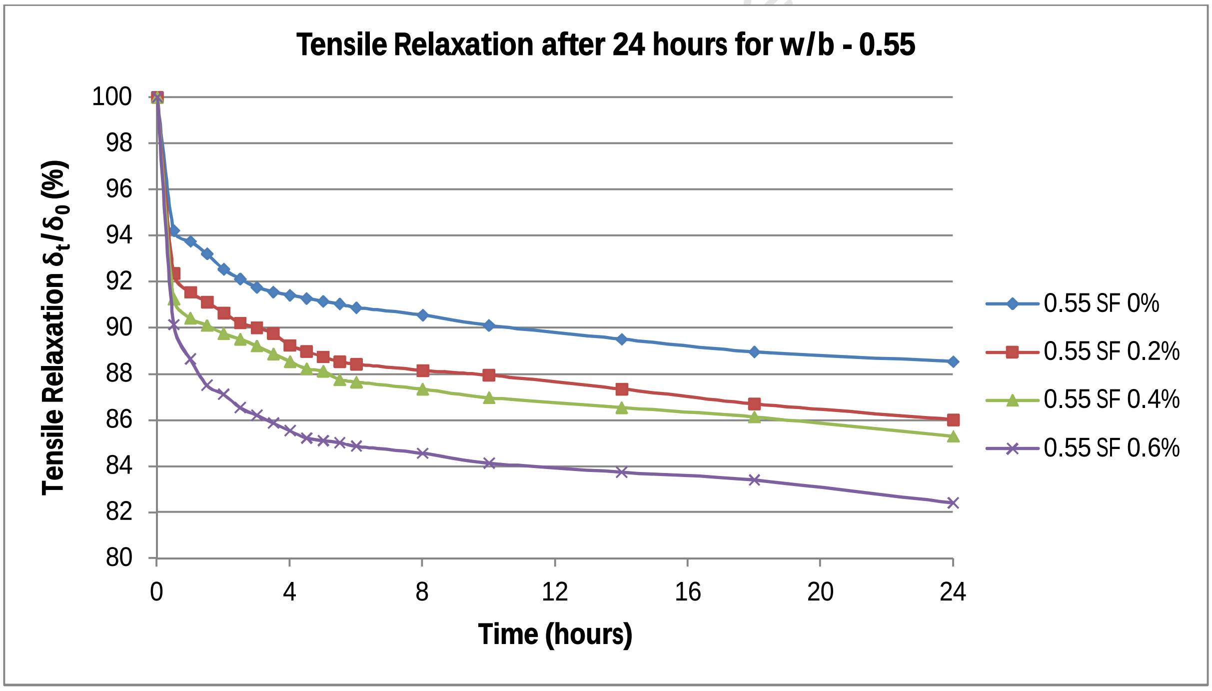

Figure 4-28: Tensile relaxation of SF samples with w/b = 0.55 over a 24 hour period

It must be noted that the tensile relaxation results shown in Figure 4.27 and 4.28 are low when compared to similar testing conducted by other researchers. Masuku (2009) performed similar testing using the same test methods and showed tensile relaxation values of approximately 30%. This author is unable to explain why the tensile relaxation values were underestimated. It was most likely due to an error in the calculation of the initial load used during the tensile relaxation testing. However, this applied to all tensile relaxation testing and the results can still be used as a method of comparing the influence of SAP's on tensile relaxation.

The results indicate that an increase in SAP content results in an increase in tensile relaxation. This is true for both w/b ratios tested. As seen below in Chapter 4.2.5, the elastic modulus of the samples tested decreases with an increase in SAP content. This is significant as a sample with a lower elastic modulus will undergo more tensile relaxation hence relieve some tensile stress that develops within the overlay.

Due to time constraints, tensile relaxation testing lasted 24 hours instead of the suggested 72 hours per sample. The justification for this decision was that most of the possible relaxation occurs within the initial 12 hours of testing. However, relaxation does still continue throughout the entire testing procedure and the 24 hour cut-off will result in less tensile relaxation occurring.

4.2.5 Elastic Modulus

The test method used for this testing is shown in Chapter 3.2.6.5. The results of the elastic modulus testing are shown in Figure 4.29.

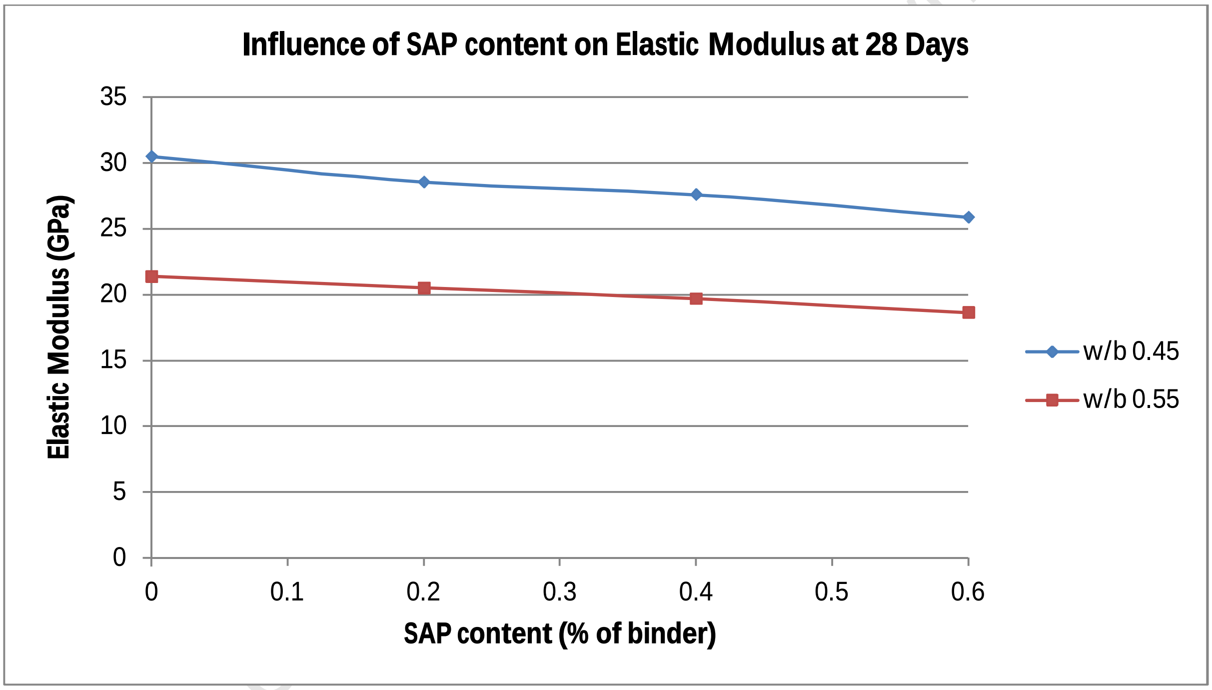

Figure 4-29: Results of elastic modulus testing for samples with w/b of 0.45 and 0.55

The elastic moduli of the samples were measured in compression at 28 days. The results of the elastic modulus testing indicate that an increase in SAP content results in a decrease in elastic modulus. A possible reason for the decrease in elastic modulus with an increase in SAP content relates to pore size and distribution. As discussed in Chapter 4.2.3.3, there is a decrease in porosity with an increase in SAP quantity. However, there is a reduction in the quantity of fine voids due to better hydration but an increase in macro pores due to the addition on SAP's. This increase in the quantity of macro pores appears to result in a decrease in elastic modulus.

The results obtained in this dissertation are consistent with the results obtained by van der Ham *et al*. Their research showed a 10% reduction in elastic modulus for samples with a w/b ratio of 0.39 and a SAP quantity of 0.4% and a 5% reduction in elastic modulus for samples with a w/b ratio of

0.32 and a SAP quantity of 0.3%. Figure 4.29 shows a reduction in elastic modulus of 9.5% and 6.4% for samples with a w/b ratio of 0.45 and a SAP content of 0.4% and 0.2% respectively.

4.2.6 Free Total Shrinkage

Free total shrinkage testing began when the samples had cured for 3 days under plastic. The test method used to measure the free total shrinkage of each mix is discussed in Chapter 3.2.6.1. The total free shrinkage is a combination of chemical, autogenous and drying shrinkage. The results of the free total shrinkage are shown in Figures 4.30 and 4.31.

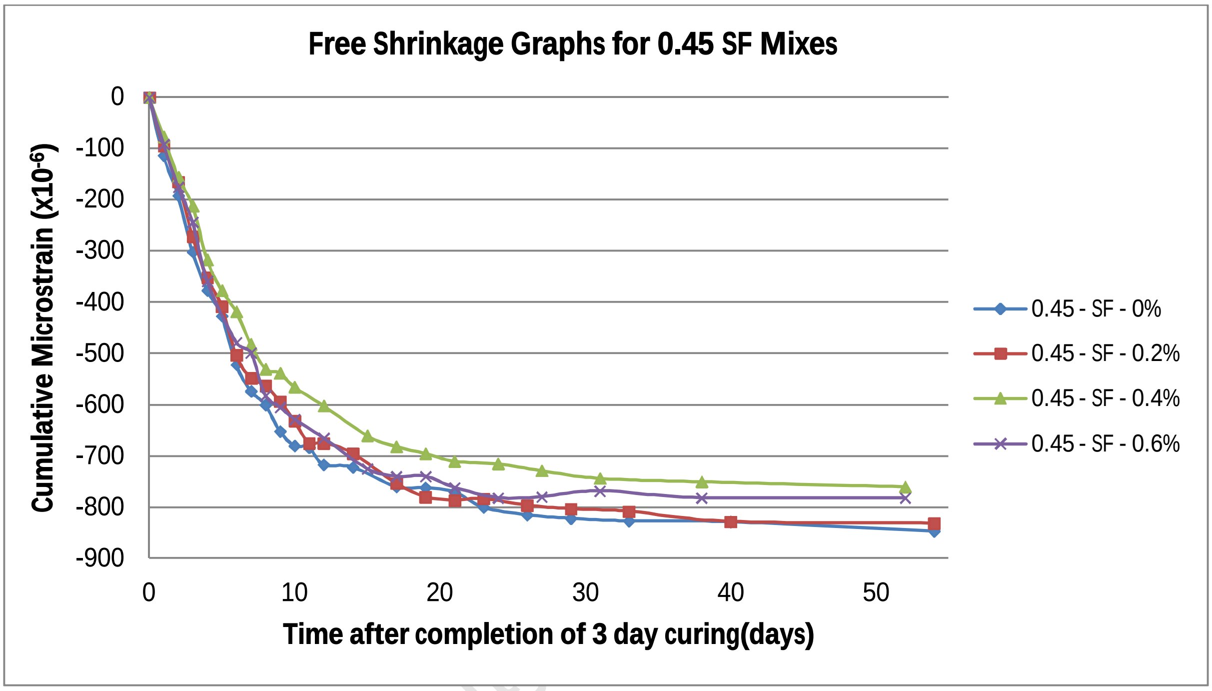

Figure 4-30: Free total shrinkage recorded for samples with a w/b of 0.45

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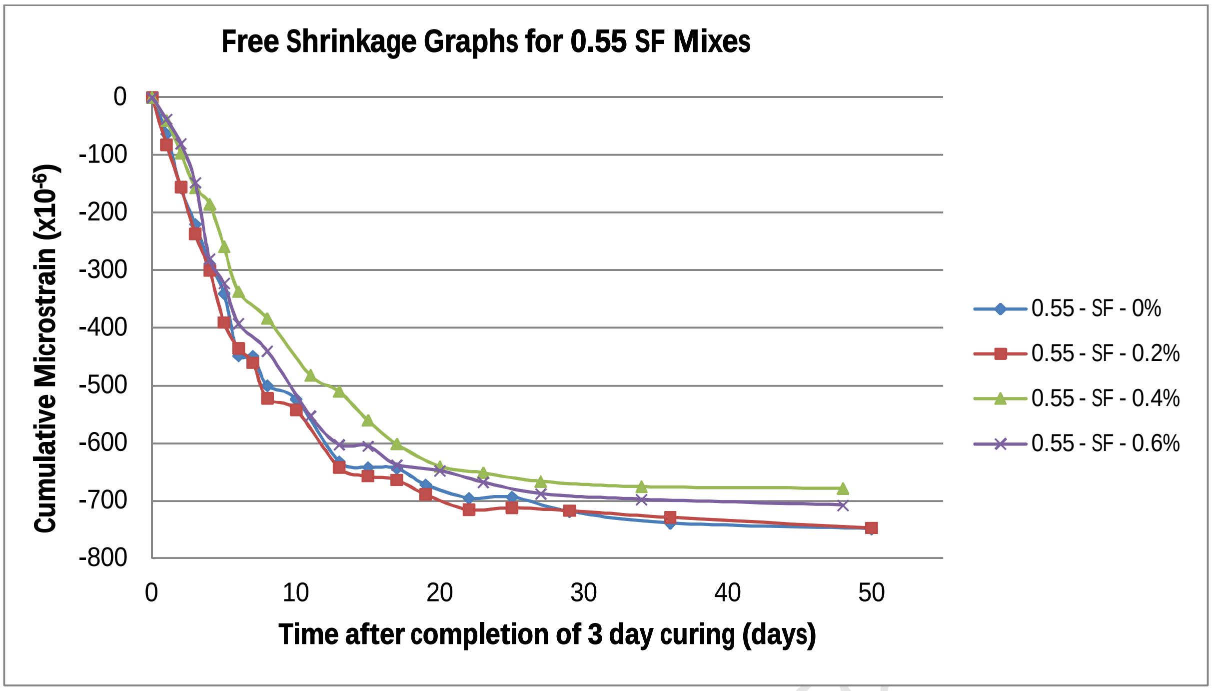

Figure 4-31: Free total shrinkage recorded for samples with a w/b of 0.45

Plastic shrinkage did not play any role in the above results. Samples were cast and cured under plastic sheeting for 3 days. Plastic shrinkage would have occurred during this time period and once the concrete had transitioned from the plastic to the solid state, it was assumed that no more plastic shrinkage would occur. Shrinkage values were only recoded on the solid prisms. Hence, the total free shrinkage values recorded were a combination of autogenous and drying shrinkage.

Literature suggests that autogenous shrinkage is directly influenced by w/b ratio: the lower the w/b ratio, the greater the effect of autogenous shrinkage. In terms of this research, more autogenous shrinkage will occur in the 0.45 w/b ratio mixes than the 0.55 w/b ratio mixes.

Literature discussed in Chapter 2.7.3.4 suggests that the addition of SAP's reduces the amount of autogenous shrinkage that occurs. Results from testing conducted by Pierard *et al*. (2006) showed that while autogenous shrinkage decreased with an increasing SAP content, drying shrinkage increased with an increasing SAP content. They reasoned that this was a result of higher moisture loss caused by the higher amount of water and the additional pore system introduced into the concrete. Pierard *et al* (2006) added additional water over and above the mix water, which would increase the quantity of water in the concrete and potentially increase shrinkage. However, in this research, no additional water was added in order to reduce shrinkage.

Drying shrinkage is greatly influenced by porosity. Drying shrinkage occurs when free mix water escapes through capillary pores and any other voids present. The results of the porosity testing shown above in Figure 4.26 show that an increase in SAP content results in a decrease in porosity. However, as discussed in Chapter 4.2.3.3, the quantity of fine, inter connected capillary pores decreases due to improved hydration. This reduction in the quantity of fine, connected capillary pores will make it more difficult for moisture to escape, hence reduce shrinkage drying shrinkage.

As discussed in Chapter 4.2.3.3, an increasing SAP content will result in an increase in the quantity of larger macro pores, which would suggest that drying shrinkage will increase. However, selection of suitable ingredients and good mix design results in the macro pores being well dispersed, reducing connectivity. This lower macro pore connectivity will further reduce the potential for drying shrinkage to occur.

Literature discussed in Chapter 2.7.3.4 suggests that in SAP content results in a decrease in autogenous shrinkage. This suggests that an increase in SAP content will result in a decrease in total shrinkage. Research conducted by Jensen & Hansen (2001) showed that a SAP content of 0.6% reduces autogenous shrinkage completely. This suggests that the mixes with an SAP content of 0.6% underwent drying shrinkage only.

The control mixes and the samples with a SAP quantity of 0.2% underwent similar shrinkage, with the test mixes having a slightly lower total shrinkage than the control after 50 days. This is true for both w/b ratios tested. Based on the literature discussed above, the control samples would have undergone more autogenous shrinkage. Both specimens had similar porosities, indicating that they should experience similar drying shrinkage. This suggests that the difference in total shrinkage between these samples is the reduction in autogenous shrinkage.

The results above show that the samples with a SAP content of 0.4% undergo less total shrinkage than the 0.6% mixes. This is true for both w/b ratios tested. The samples with a SAP content of 0.6% also have a lower porosity than the samples with a SAP content of 0.4%, suggesting that the 0.6% mixes should undergo less drying shrinkage and zero autogenous shrinkage, hence having the lowest total shrinkage. The results of this testing do not indicate this and this author cannot explain why. However, the general trend suggests that an increase in SAP results in a decrease in total shrinkage. This agrees with the outcomes of research conducted by Pierard *et al* (2006), Jensen & Hansen (2001) and Mechtcherine *et al* (2006).

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4.2.7 Restrained Shrinkage

Repair overlays were cast onto an infinitely rigid substrate, as discussed in Chapter 3.2.6.2. The overlays were visually assessed daily to monitor any crack propagation. The visible crack path was highlighted with a red marker pen in order to monitor any further cracking. The results are shown in Figures 4.32 and 4.33.

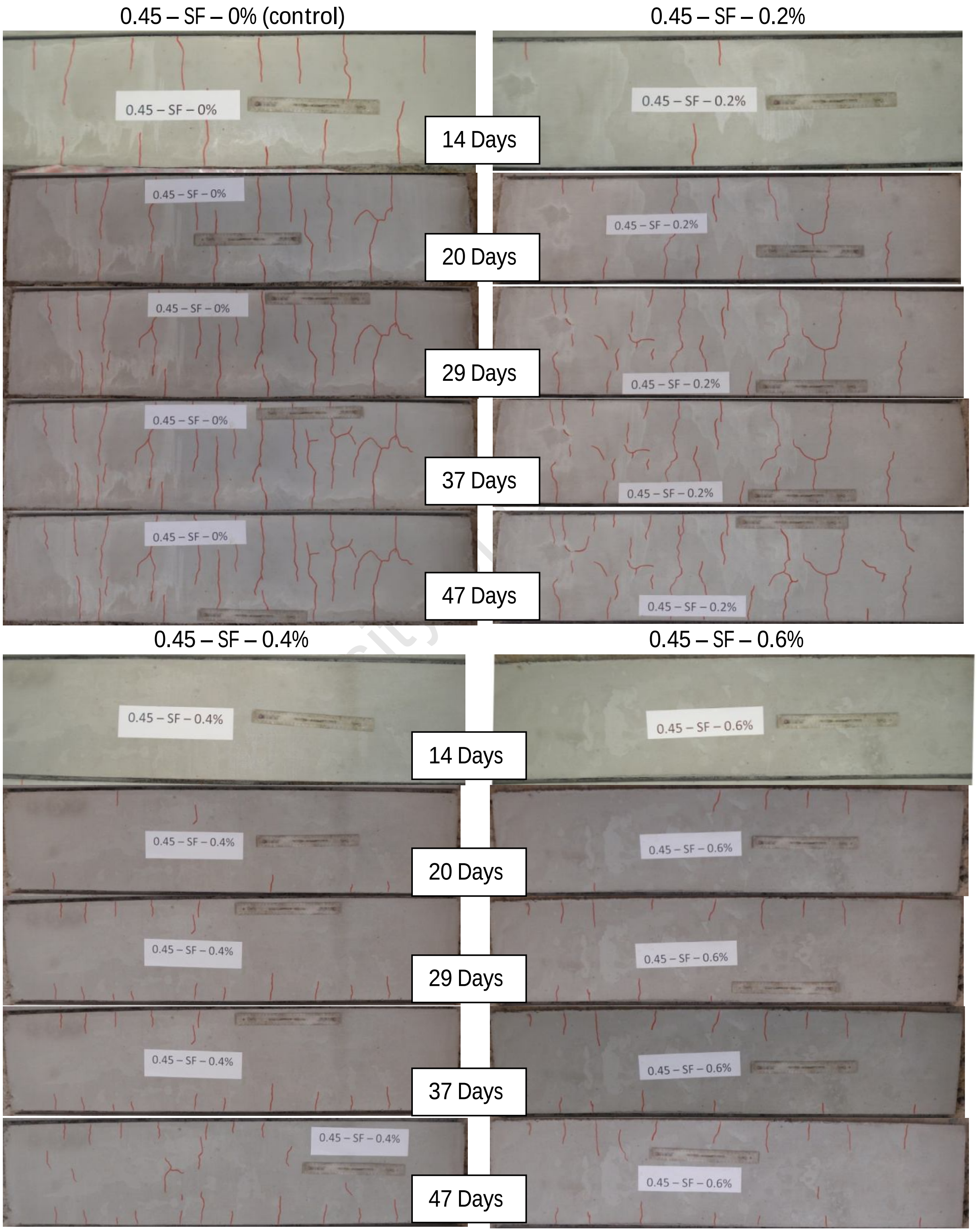

Figure 4-32: Visual recording of crack propagation of the 0.45w/b SF mixes over 47 days (30 cm ruler for scale)

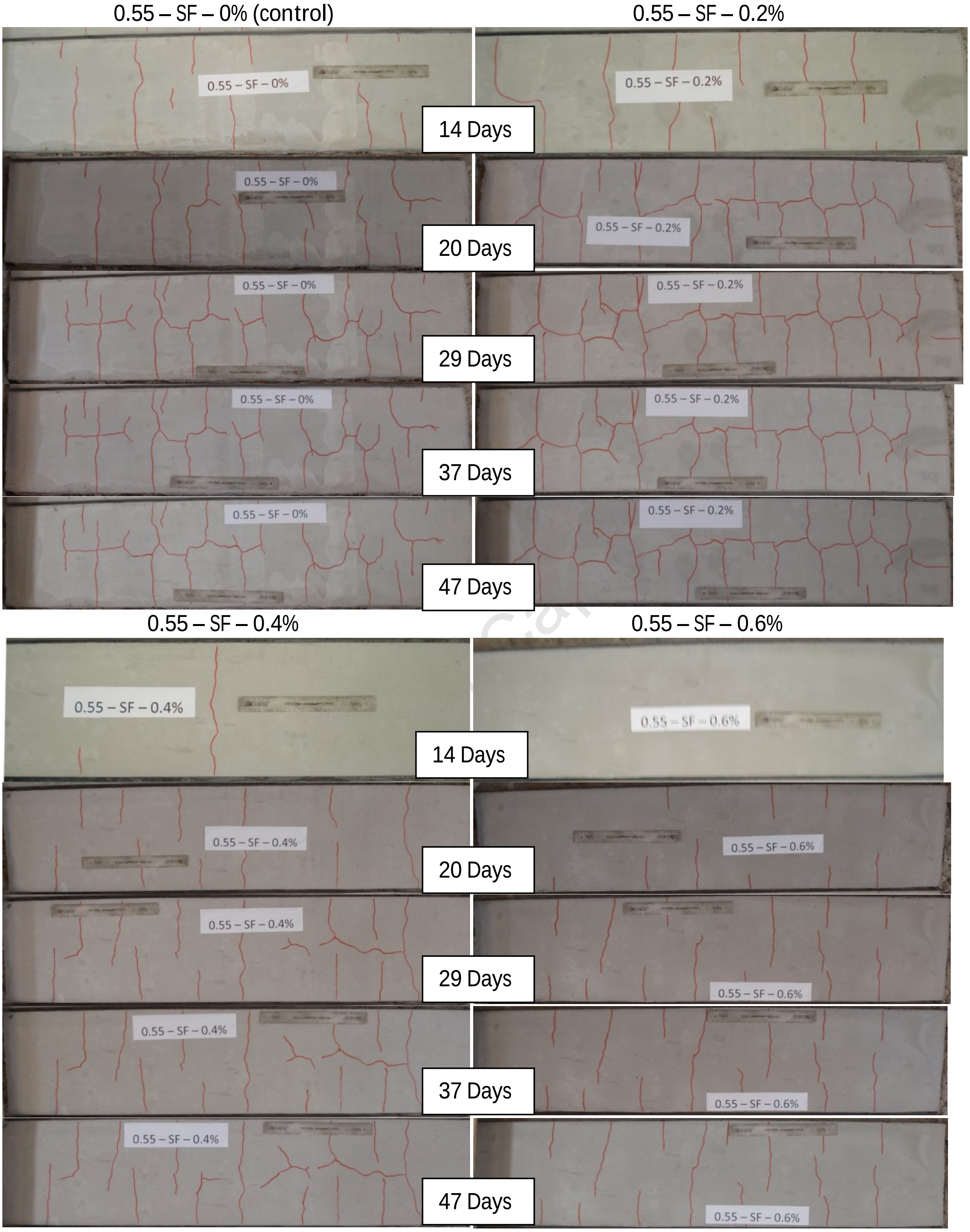

Figure 4-33: Visual recording of crack propagation of the 0.55w/b SF mixes over 47 days (30 cm ruler for scale)

Figure 4.32 and 4.33 show a clear indication of how the addition of SAP's to repair mortars can improve their performance, which is the subject of this dissertation. Two clear trends can be seen: a lower w/b ratio and an increase in SAP content decreases overlay cracking.

The cracking of these samples must be seen in context as they were designed to crack. The overlays above were long and slender, which encouraged them to crack transversely. When assessing the repair overlays, it is clear to see that the test specimens outperformed the control sample.

The samples containing 0.6% SAP had fewer cracks after 47 days than the control sample had after 14 days. This is true for both w/b ratios tested. The cracks visible in the samples containing 0.4% SAP took significantly longer to develop than the control and sample containing 0.2% SAP.

The control and the sample containing 0.2% SAP had similar crack developments at similar ages for both w/b ratios of 0.45 and 0.55. The above mentioned results can be attributed to a number of factors.

Even though the samples had similar compressive strengths at 28 days, the samples containing SAP's had a higher tensile strength with an increasing SAP content. This increase in strength could potentially have allowed these repair mortars to resist any tensile stresses that developed at early ages.

Beushausen and Alexander (2006) showed that elastic modulus influences resistance to shrinkage cracking. An increase in elastic modulus increases overlay stresses which in turn depend on relaxation. The samples containing SAP's had a decreasing elastic modulus with an increasing SAP content. This lower rigidity would have allowed the repair mortars containing SAP's more movement, which in turn would reduce any tensile stresses within the repair overlay, hence reducing the potential for cracking.

The results of the tensile relaxation testing indicated that an increase in SAP content resulted in an increase in tensile relaxation. Tensile relaxation allows for the release of any tensile stresses building up within the repair without compromising the repair mortar's performance. This increase in relaxation would decrease the chances of the repair mortar cracking.

The results of the free shrinkage tests indicate that samples containing a larger quantity of SAP had slightly less total shrinkage than the controls. The total shrinkage of the control sample and the samples containing 0.2% SAP for both w/b ratios of 0.45 and 0.55 had similar free shrinkage results, which were higher than the samples with a SAP content of 0.4 and 0.6%. The larger total shrinkage values for the control and the mixes containing 0.2% SAP indicate that they would have had similar tensile stresses within their structure. This could explain why these samples had similar crack developments at similar ages. Literature also suggests that the optimal SAP content is between 0.35 and 0.4% of the total binder quantity. A SAP content of only 0.2% could be too low for the repair mortar to gain the benefits associated with SAP's mentioned above.

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4.2.8 Shear Bond Strength

The method used for the shear bond strength test is discussed in Chapter 3.2.6.3. Tests were conducted on 150 x 150mm samples at ages of 3, 7 and 28 days. The results of these tests are shown in Figures 4.34 – 4.35.

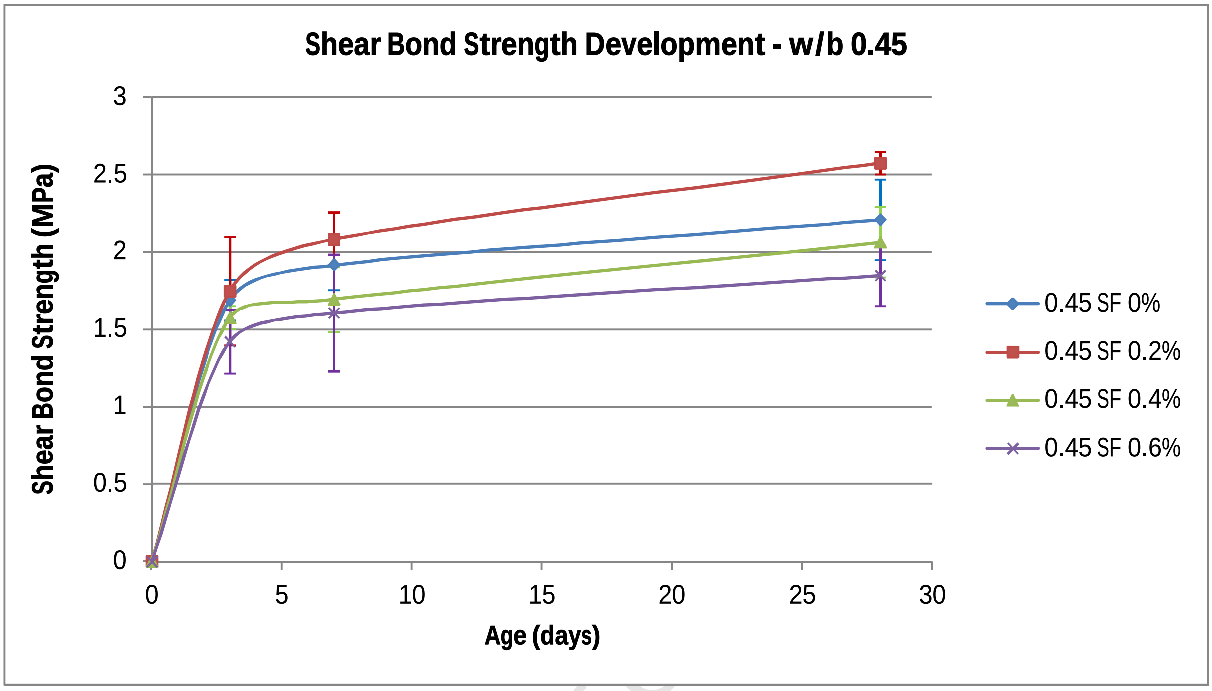

Figure 4-34: Shear strength development over time for w/b 0.45 samples

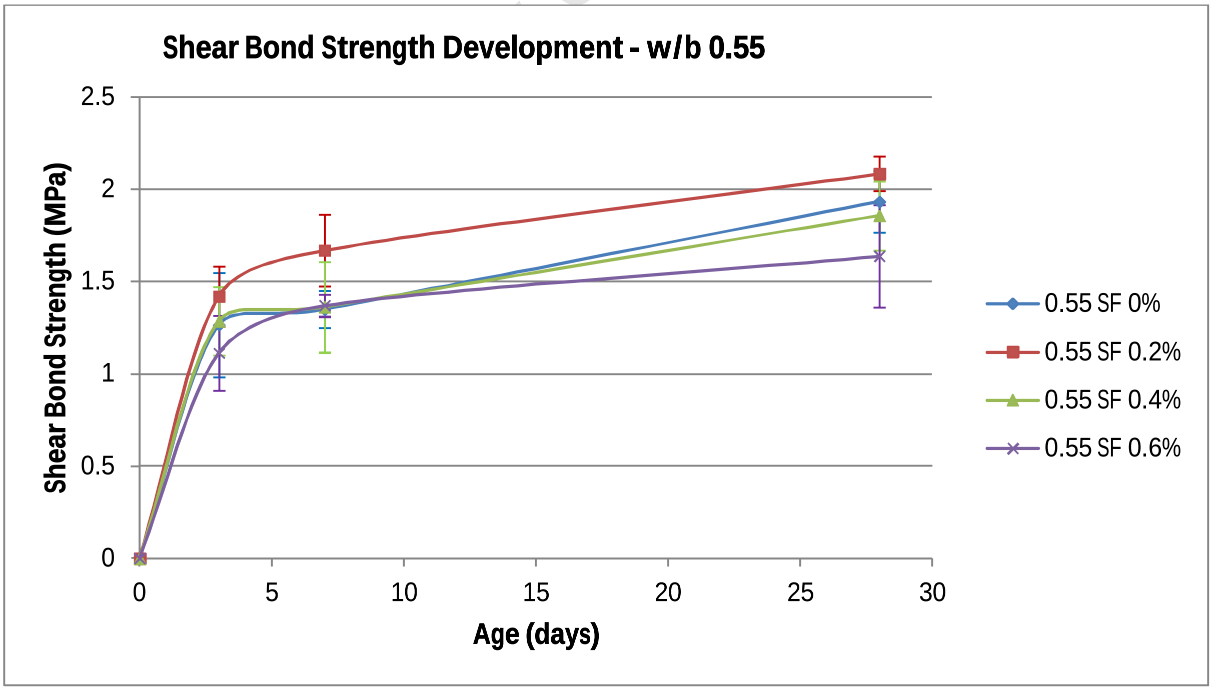

Figure 4-35: Shear strength development over time for w/b 0.55 samples

The results of the shear bond strength indicate that the bond strength is affected by testing age and w/b ratio. As literature suggests, there is an increase in bond strength with an increase in age. The w/b ratio also influences the bond strength, as the lower the w/b ratio, the higher the shear bond strength.

There is also a clear trend visible in terms of shear bond strength and SAP quantity. The mixes with a SAP content of 0.2% had the highest shear bond strength for each w/b ratio tested at 3, 7 and 28 days. Possible reasons for this are discussed below.

The control samples had more free mix water available than the samples with a SAP content of 0.2% as the SAP particles absorbed some free additional mix water. The shear bond specimens were cast onto dry substrates. These dry substrates would have absorbed some of the free mix water, which in theory should reduce the w/b ratio, which in turn should improve the bond. However, if too much free mix water is absorbed, there would be too little water available for the hydration reaction to occur and as such would reduce the bond strength between the overlay and the substrate.

The addition of 0.2% SAP to the repair overlay would have allowed the overlay to keep some of the free mix water within the SAP particles. This water would have been kept in the SAP particles by van der Waals forces and would not have been absorbed by the substrate. This would have resulted in more water being available for the hydration reaction, resulting in more products of hydration, which would increase the bond strength between the overlay and the substrate.

According to the paragraph above, an increasing SAP content should result in better bond strength. However, the results of this testing do not reflect this theory. An increase in SAP content resulted in the mixes being more difficult to compact due to less free water being available in the mix. This is a possible reason for the decreasing shear bond strength values for the mixes with a w/b of 0.4 and 0.6%. The compaction of the overlay is important in order to obtain a homogenous overlay which can help fulfil the requirement for repaired or modified structures to behave monolithically. Furthermore, effective compaction can help to eliminate the development of air pockets and ensure uniform interfacial bond (Silfwerbrand & Beushausen, 2006). The difficulty associated with compacting these mixes could have thus reduced the shear bond strength.

As discussed in Chapter 2.3.3.2, shear bond failure generally occurs in the overlay interface zone. This usually involves failure along the concrete interface and in the substrate and overlay to a depth generally not exceeding 5mm. The location of the shear failure can be a good indication of the quality of bond developed. All samples tested failed at the concrete interface, indicating poor mechanical interlock. The presence of microcracks and poor mechanical interlock are consistent with samples with low shear bond strength.

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5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Most concrete structures deteriorate over time due to exposure to environmental conditions. This has resulted in a large number of concrete structures in South Africa either approaching the end of their service life or needing rehabilitation. Bonded concrete overlays remain a prominent tool used for repairing deteriorated concrete structures.

Differential shrinkage is often the main problem affecting performance of bonded overlays. Differential shrinkage is caused by autogenous and drying shrinkage and tensile stresses develop in the overlay as a result of differential shrinkage. Tensile overlay stresses may lead to cracking and /or debonding.

Cracking and debonding of bonded concrete overlays may be prevented if tensile stresses are reduced to levels below that of overlay tensile strength. This can be achieved by reducing shrinkage, increasing overlay tensile strength or by increasing in tensile relaxation.

Superabsorbent polymers (SAP's) are a relatively new ingredient for use in concrete and research has focussed on their application mainly to high performance concrete. However, very little research has been conducted in the use of SAP's to improve repair overlays.

The outcomes of this investigation into the use of SAP's in repair materials serves as an important contribution towards determining how the use of SAP's can improve concrete overlay performance. This investigation explored the influence of SAP's on key characteristics influencing concrete overlay performance and analysed some beneficial or detrimental effects.

The beneficial properties of SAP's can potentially improve bonded concrete overlay performance. One of the most noticeable benefits of using SAP's is the increase in tensile strength. Any tensile strength improvement can greatly reduce the risk of early age cracking. In addition to the increase in tensile strength, tensile relaxation increased with an increase in SAP content. Greater tensile relaxation capacity will allow tensile stresses to be released, decreasing the stresses present within the system and hence reduce the risks of debonding and cracking.

Mitigating shrinkage can greatly reduce the stresses that develop within the overlay system, hence reducing the risk of cracking. The addition of SAP's reduces shrinkage within the overlay system. The rate of drying shrinkage was reduced, which further reduced the risk of cracking whilst allowing sufficient time for tensile strength development.

The above benefits were clearly visible on the overlays cast on the laboratory floor, which clearly showed that an increase in SAP content decreased the extent of cracking. This was a result of the increase in tensile strength and tensile relaxation, the decreased elastic modulus and the reduction of shrinkage. All these factors in combination indicate that the use of SAP's in repair overlays has some potential to improve overlay performance.

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5.2 Summary of main conclusions

In general, the addition of SAP's influenced the performance of bonded concrete overlays both positively and negatively. The varying impacts of SAP's on overlay performance are summarised below.

5.2.1 Influence of SAP quantity on material properties

The quantity of SAP added influenced various material properties in a varying manner. The porosity results indicated that an increase in SAP quantity resulted in a decrease in porosity. An increase in SAP content decreases the porosity of the samples tested as per the UCT durability index test methods. This is the result of a decrease in finer capillary pores due to improved hydration and less connectivity of the larger macro pores. This is true for both w/b ratios tested in this research.

5.2.2 Influence of SAP's on different w/b ratios

The results of this research suggest that the addition of SAP's have a more pronounced influence on samples with a higher w/b ratio. The addition of SAP's to samples with a w/b ratio of 0.45 had little influence in terms of durability but showed more improvement in samples with a w/b ratio of 0.55. The above trend was also true for tensile relaxation and free shrinkage testing.

5.2.3 Influence of SAP's on compressive and tensile strength development

The addition of SAP's did not decrease the compressive strength of samples with a w/b ratio of 0.45. This was true for all ages tested. The samples with a w/b ratio of 0.55 showed that the addition of SAP's decreased compressive strength slightly at early ages but had similar strengths after 28 days. The results obtained in this research agree with the results obtained by Monnig & Reinhardt (2006) and Lura *et al* (2006) which states that the addition of SAP's does not negatively impact of compressive strength. This is most likely due to the increase in hydration products counteracting any negative impact of the increase in larger pores within the cement matrix

The tensile strength results showed that an increase in SAP content resulted in an increase in tensile strength. This was true for both w/b ratios tested at all ages. These results agree with research conducted by Lam (2005), which also showed an increase in tensile strength with an increasing SAP content. This is most likely due to an increase in hydration products. This is significant as an increase in tensile strength, especially at early ages, can decrease the risk of overlay cracking.

5.2.4 Influence of SAP's on durability

The addition of SAP's did not negatively impact on the permeability and carbonation resistance of samples with a w/b ratio of 0.45. However, an increase in SAP content resulted in a decrease in permeability and increase in carbonation resistance of samples with a w/b ratio of 0.55.

The above trend was also observed for the results of the chloride conductivity and bulk diffusion testing. This suggests that the addition of SAP's to samples with a w/b ratio of 0.55 greatly improves durability.

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5.2.5 Influence of SAP's on tensile relaxation

The addition of SAP's had a positive influence on tensile relaxation. Both w/b ratios tested showed that an increasing SAP quantity resulted in an increase in the quantity of tensile relaxation that occurred. This is of significance for bonded concrete overlays as tensile relaxation relieves tensile stresses that develop within the overlay. An increase in tensile relaxation will reduce the chance of overlay cracking.

5.2.6 Influence of SAP's on shrinkage

The addition of SAP's did not influence the total quantity of free shrinkage that occurred for both w/b ratios considered. Both w/b ratios considered during this testing showed similar free shrinkage at later ages.

However, an increase in SAP content resulted in a decrease in the rate of drying shrinkage occurring at early ages. This is due to any free water available in the samples being held within the SAP particles. This is of significance as reducing early age shrinkage will reduce the tensile stresses that develop at early ages, when overlays are most vulnerable to cracking. This is most likely due to the SAP particles holding any additional free water within its own structure, which would prevent it from escaping, hence decreasing drying shrinkage.

5.2.7 Influence of SAP's on shear bond strength

The addition of SAP's in small quantities improves the shear bond strength between concrete substrate and overlay when 0.2% SAP is added, but decreases with any further increase in SAP content. The addition of SAP's increases hydration as well as prevents moisture loss to the substrate, hence improving bond strength. However, an increase in SAP content reduces the workability of the overlay, making compaction difficult. Poor compaction will result in air pockets at the bond interface, which reduces shear bond strength.

5.3 Recommendations

The results of this research indicate that the addition of SAP's can potentially improve some characteristics of bonded concrete overlays. However, the potential benefits are more pronounced at higher w/b ratios. This researcher recommends that repair mortars with a w/b ratio of 0.55 should be used with SAP's.

This research identified effects of some main aspects affecting bonded concrete overlay performance. This research investigated how SAP's can be used to overcome some of the problems associated with concrete overlays. However, it did not investigate any of the major factors influencing overlay performance in detail. For a deeper understanding of how SAP's can be used to improve bonded concrete overlay performance, the following aspects should be considered:

- The focus of this research was to determine if the addition of SAP's have the potential to improve bonded concrete overlay performance as patch repairs. Due to the large number of tests that were required, testing was limited to 2 w/b ratios with differing SAP contents. Further testing is proposed varying w/b ratio, SAP content and substrate surface preparation. W/b ratios of 0.55 and above should be tested.

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- Research should be done to determine the impact of using different fine and coarse aggregates. This research focussed on mortars only and there is a need to investigate typical concrete mixes commonly used in bonded concrete overlays.

- The results of the tensile relaxation testing showed that the addition of SAP's can increase tensile relaxation. However, this research underestimated the tensile relaxation due to an error in the initial load applied to the samples. Further, detailed tensile relaxation testing is proposed.

- Bonded overlays cast on the laboratory floor demonstrated the benefits of using SAP's in overlays. Research focused on mitigating or reducing drying shrinkage at early ages as well as tensile strength should be conducted to further investigate the potential benefits of using SAP's in repair materials.

- This research only considered one curing regime. Further testing involving different curing regimes should be considered in order to determine any additional benefits associated with the addition of SAP's to repair materials.

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Appendix A
Shear Bond Strength Test Apparatus

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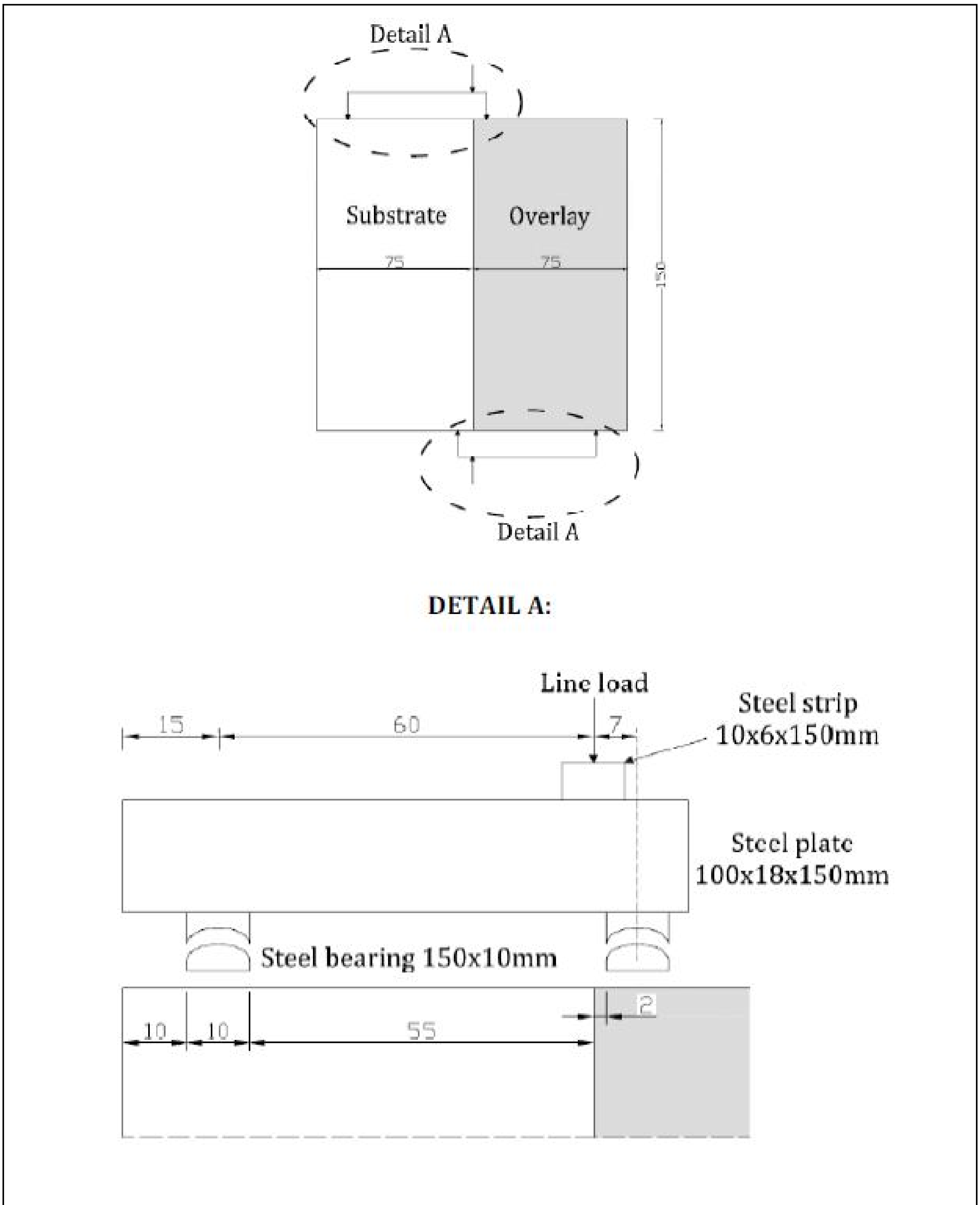

Figure A1: Shear bond strength test apparatus

Appendix B

Results of Initial Testing

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Compressive Strength Results

Table B1: Compressive Strength Results at 3 days

3 Day Compressive Strength (MPa)								
	w/b -0.45				w/b -0.55			
Extender	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
FA	17.4	20.4	19.5	19.0	12.7	14.5	11.1	10.4
GGBS	13.7	15.3	14.2	13.4	10.0	5.1	7.1	7.6
SF	29.2	29.3	27.3	29.4	20.3	17.7	17.7	17.3

Table B2: Compressive Strength Results at 7 days

7 Day Compressive Strength (MPa)								
	w/b -0.45				w/b -0.55			
Extender	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
FA	27.8	28.9	27.0	27.1	19.0	21.9	18.0	18.0
GGBS	28.3	27.0	25.8	25.3	20.1	12.5	16.0	18.8
SF	38.5	39.7	37.1	40.0	29.4	27.6	27.1	26.9

Table B3: Compressive Strength Results at 3 days

28 Day Compressive Strength (MPa)								
	w/b -0.45				w/b -0.55			
Extender	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
FA	39.5	42.2	42.6	39.4	28.6	32.3	26.2	25.7
GGBS	48.9	48.6	46.0	45.9	35.6	25.9	31.4	37.9
SF	54.3	56.3	54.0	56.3	41.8	40.9	40.8	39.7

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Tensile strength Results

Table B4: Tensile Strength Results at 3 days

3 Day Tensile Strength (MPa)								
	w/b -0.45				w/b -0.55			
Extender	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
FA	1.87	1.86	1.57	1.57	1.19	1.22	1.05	0.95
GGBS	0.81	0.64	1.09	1.02	0.79	0.77	0.87	0.69
SF	1.93	2.38	2.01	1.92	1.56	1.69	1.38	1.26

Table B5: Tensile Strength Results at 14 days

14 Day Tensile Strength (MPa)								
	w/b -0.45				w/b -0.55			
Extender	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
FA	2.25	2.81	2.25	2.18	2.01	1.79	1.69	1.41
GGBS	1.58	2.07	2.43	2.55	1.48	1.89	2.13	2.04
SF	2.53	2.89	3.32	2.58	2.13	1.82	2.18	2.49

Durability Results

Table B6: OPI results

OPI								
Extender	w/b -0.45				w/b -0.55			
	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
FA	10.56	10.40	10.00	10.19	9.67	10.03	9.87	9.86
GGBS	10.60	10.42	10.14	10.37	9.88	9.92	10.07	10.02
SF	10.38	10.30	10.42	10.40	9.92	10.16	10.06	10.28

Table B7: Chloride Conductivity Results

Chloride Conductivity (mS/cm)								
Extender	w/b -0.45				w/b -0.55			
	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
FA	1.95	1.10	0.86	0.85	2.04	1.76	2.03	2.04
GGBS	0.33	0.24	0.31	0.30	0.58	1.01	0.75	0.68
SF	0.36	0.33	0.40	0.28	1.03	1.02	0.87	0.55

Table B8: Sorptivity Results

Sorptivity (mm/$h^{0.5}$)								
Extender	w/b -0.45				w/b -0.55			
	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
FA	7.20	6.39	6.27	5.61	7.85	8.47	7.70	6.39
GGBS	6.13	6.52	6.46	5.32	6.70	8.02	6.32	5.52
SF	5.76	5.78	5.09	4.73	5.65	5.88	5.40	3.87

Table B9: Porosity Results

Porosity (%) (measured from OPI test)								
Extender	w/b -0.45				w/b -0.55			
	0%	0.2%	0.4%	0.6%	0%	0.2%	0.4%	0.6%
FA	14.46	14.13	13.56	13.78	16.30	14.96	15.94	17.29
GGBS	10.31	9.41	10.59	10.62	12.69	12.54	11.96	12.35
SF	11.05	10.37	10.81	9.65	15.59	14.28	14.60	11.25

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Appendix C

Results of Further Testing on SF Mixes

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Compressive Strength Results

Table C1: Compressive strength results

Sample Age (Days)	Compressive Strength (MPa)							
	w/b - 0.45				w/b - 0.55			
	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
3	29.2	29.3	27.3	29.4	20.3	17.7	17.7	19.2
7	38.5	39.7	37.1	40	29.4	27.6	27.1	31.2
28	54.3	56.3	54.0	56.3	41.8	40.9	40.8	39.7

Tensile Strength Results

Table C2: Tensile Strength Results

Sample Age (days)	Tensile Strength (MPa)							
	w/b -0.45				w/b -0.55			
	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
3	1.75	2.03	1.92	1.94	1.48	1.68	1.51	1.65
7	1.78	2.04	2.20	2.35	1.51	1.66	1.60	1.72
14	2.73	3.11	3.22	3.29	2.11	2.22	2.51	2.91

Durability Summary

Table C3: OPI Results

OPI Results							
w/b -0.45				w/b -0.55			
0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
10.38	10.30	10.42	10.40	9.92	10.16	10.06	10.28

Table C4: Carbonation Depth Results

Carbonation Depth (mm)							
w/b -0.45				w/b -0.55			
0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
1.6	1.4	1.3	1.1	6.0	4.5	3.4	3.3

Table C5: Chloride Conductivity Results

Chloride Conductivity (mS/cm)							
w/b -0.45				w/b -0.55			
0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
0.36	0.33	0.40	0.28	1.03	1.02	0.87	0.55

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Table C6: Bulk Diffusion Results

Diffusion Coefficient (Dc x 10^{-12})							
w/b -0.45				w/b -0.55			
0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
8.33	7.33	6.02	4.64	12.66	10.82	9.82	8.99

Table C7: Porosity Results

Porosity (%)							
w/b -0.45				w/b -0.55			
0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
11.05	10.37	10.81	9.65	15.59	14.28	14.60	11.25

Tensile Relaxation Result

Table C8: Tensile relaxation Results

Tensile Relaxation (δ_t/δ_0) (%)							
w/b -0.45				w/b -0.55			
0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
10.2	10.9	12.2	15.5	11.5	14.0	14.7	17.6

Elastic Modulus Results

Table C9: Elastic Modulus Results

Elastic Modulus (GPa)							
w/b -0.45				w/b -0.55			
0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
30.5	28.6	27.6	25.9	21.4	20.5	19.7	18.6

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Free Shrinkage Results

Table C10: Free Shrinkage Results of 0.45 w/b samples

Free Shrinkage (x 10^{-6})							
0.45 - SF - 0%		0.45 - SF - 0.2%		0.45 - SF - 0.4%		0.45 - SF - 0.6%	
Age (days)	Microstrain	Age (days)	Microstrain	Age (days)	Microstrain	Age (days)	Microstrain
0	0	0	0	0	0	0	0
1	-113	1	-95	1	-77	1	-92
2	-192	2	-165	2	-155	2	-175
3	-302	3	-272	3	-212	3	-243
4	-377	4	-352	4	-317	4	-358
5	-427	5	-408	5	-377	6	-478
6	-522	6	-503	6	-418	7	-498
7	-573	7	-548	7	-482	8	-582
8	-600	8	-563	8	-530	9	-605
9	-652	9	-593	9	-538	10	-628
10	-680	10	-632	10	-565	12	-665
11	-683	11	-675	12	-602	15	-725
12	-717	12	-675	15	-660	17	-740
14	-722	14	-695	17	-682	19	-740
17	-760	17	-753	19	-695	21	-762
19	-762	19	-780	21	-710	24	-782
21	-770	21	-787	24	-715	27	-780
23	-800	23	-783	27	-728	31	-768
26	-815	26	-797	31	-743	38	-782
29	-822	29	-803	38	-750	52	-782
33	-827	33	-808	52	-760		
40	-828	40	-828				
54	-847	54	-832				

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Table C11: Free Shrinkage Results of 0.55 w/b samples

Free Shrinkage (x 10^{-6})							
0.55 - SF - 0%		0.55 - SF - 0.2%		0.55 - SF - 0.4%		0.55 - SF - 0.6%	
Age (days)	Microstrain	Age (days)	Microstrain	Age (days)	Microstrain	Age (days)	Microstrain
0	0	0	0	0	0	0	0
1	-63	1	-82	1	-40	1	-38
2	-157	2	-155	2	-97	2	-80
3	-220	3	-237	3	-157	3	-148
4	-288	4	-300	4	-185	4	-280
5	-340	5	-390	5	-258	5	-323
6	-448	6	-435	6	-337	6	-393
7	-448	7	-460	8	-383	8	-440
8	-500	8	-522	11	-482	11	-553
10	-523	10	-542	13	-510	13	-603
13	-632	13	-642	15	-560	15	-605
15	-642	15	-657	17	-601	17	-638
17	-643	17	-663	20	-640	20	-648
19	-672	19	-688	23	-651	23	-668
22	-695	22	-715	27	-666	27	-688
25	-693	25	-712	34	-675	34	-698
29	-718	29	-717	48	-678	48	-708
36	-738	36	-728				
50	-748	50	-747				

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Shear Bond Strength Results

Table C12: Shear Bond Strength Results

Sample Age (Days)	Shear Strength (MPa)							
	w/b - 0.45				w/b - 0.55			
	0%	0.20%	0.40%	0.60%	0%	0.20%	0.40%	0.60%
3	1.69	1.75	1.58	1.42	1.27	1.42	1.29	1.11
7	1.92	2.08	1.69	1.61	1.35	1.67	1.36	1.37
28	2.21	2.57	2.06	1.85	1.93	2.09	1.86	1.64