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Faculty of Engineering and the Built Environment

Department of Civil Engineering

EVALUATION OF SURFACE TREATMENTS FOR RC STRUCTURES FAILING TO MEET SOUTH AFRICAN DURABILITY INDEX REQUIREMENTS

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Abstract

In many countries the budget for repairing existing infrastructure already exceeds that of building new infrastructure. The main durability problem is corrosion of reinforcing steel caused by the ingress of aggressive agents and moisture. The South African durability index approach makes use of indices to evaluate the potential durability of concrete. Once limiting values on the as built structure meet specific requirements, the structure is considered to be inherently durable. However, a clear design methodology or guidelines for concrete structures that do not meet the specified minimum requirements needs to be established.

The potential for using surface treatments to prevent the ingress of corrosion causing agents (carbon dioxide, chloride ions and moisture) is presented in literature but the extent of protection and durability of these products is largely unknown. A laboratory investigation was developed to evaluate the performance and longevity of surface treatments under accelerated weathering and exposure conditions. Poor quality concrete failing to meet durability requirements was treated with six products and exposed to accelerated weathering conditions. The carbon dioxide and chloride ion resistance was then evaluated to establish performance and durability characteristics for each of the products.

Results indicate that surface treatments restrict the passage of deleterious agents and certain products can be used as an acceptable method of corrosion prevention. The pure silane coating was found to effectively reduce the ingress of chlorides while the acrylic dispersion, acrylic resin, cement based and cement based fibre reinforced coatings were effective in preventing carbonation. Furthermore, it was found that the increased service life due to the application of anti-carbonation coatings could be quantified with a specific number of years. Service life quantification due to improved chloride ion resistance was not possible since modified and custom tests differing from the standard bulk diffusion test were used to evaluate performance. Chloride resistance was improved due to the pure silane however service life improvements could not be quantified.

Unexpected failures occurred during the laboratory investigation rendering a number of tests inconclusive. Some guidance based on the knowledge gained during this project is provided for future testing.

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1 Introduction

1.1 Background

The durability of structures is primarily a function of permeability and the ease at which liquids and gasses are transported through concrete. Thus, the service life structures is heavily dependent on the permeability and the rate at which aggressive ions and molecules may enter and move through concrete. The most significant cause of reinforced concrete deterioration is carbonation and chloride induced corrosion (Richardson, 2002; Alexander et al 2008).

In the early 1990's, a research project was started that was to improve the quality of reinforced concrete construction in South Africa. Particular attention was given to the premature corrosion of reinforcing steel caused by the ingress of harmful agents. The South African durability index approach uses carbonation and chloride ingress models to predict the service life of reinforced concrete structures. In past years, strength has been the main design criterion for concrete structures. Durability however is widely affected by different proportioning, placing and curing conditions. Therefore, while strength is recognised as an important design parameter, durability is also an important design consideration of reinforced concrete. The South African durability approach specifies limiting values on parameters affecting the movement of deleterious substances through concrete. Recently, these limiting values have been adopted into the specification of structural concrete in much the same way strength is specified (Alexander et al, 2007).

The South African National Roads Agency Limited (SANRAL) has included durability indices in specifications for concrete design. Acceptance criteria have been given for limiting values of water sorptivity, oxygen permeability and chloride conductivity. Similarly, guidelines have been given for the acceptance of concrete cover. Additionally, guidance has been provided for designers and contractors in order to clarify liability.

Making use of the South African durability index approach models for carbonation and chloride ingress, engineers are able to predict the expected service life of reinforced concrete. Once concrete has been tested and met the durability requirements specified by the South African durability index approach then it is considered to be inherently durable. However, a clear design methodology for concrete structures that do not meet the specified requirements needs to be established. Under such conditions, a number of avenues could be pursued to compensate for the expected service life reduction including financial penalties, remedial work and (under extreme circumstances) complete rejection. From a technical standpoint, various surface treatments to improve the durability characteristics of poor quality concrete are available for use.

The performance and durability of concrete coatings has been assessed in a number of investigations. Analysis under a range of conditions has been carried out on various generic coating types. Assessment methods and exposure conditions have been inconsistent over a range of studies. Currently, standard performance indicators of performance and durability of coatings and coating systems are lacking. Furthermore, product properties from different manufacturers vary across the generic groups to which they belong. Thus, generalised performance specifications of generic coating groups should be followed prudently by engineers.

With careful planning and selection, the long-term performance of reinforced concrete structures can be ensured with concrete surface treatments. However, a regular maintenance schedule should also be implemented and followed to guarantee continued protection.

1.2 Motivation for research

A large proportion of the national budget in modern economies is spent on repairing structures that are failing because of corroding reinforcing steel because of inadequate concrete quality (Emmons and Vaysburd, 1996). In recent times, it has become clear that the durability of reinforced concrete structures is an important design consideration. For years, little attention has been given to durability and design has largely been focused on the safety and serviceability of concrete structures. The main durability problem is the corrosion of reinforcing steel caused by the ingress of aggressive agents and moisture. When aggressive agents such as carbon dioxide and chloride ions enter concrete, depassivation of the reinforcing steel may occur and if moisture is present, corrosion may proceed (Richardson, 2002).

The South African durability index approach makes use of indices to evaluate the potential durability of concrete. Although the South African durability index approach does not measure the actual penetrability of corrosive agents directly, it measures certain transport properties that can be linked to the penetration of corrosive agents. Equipped with knowledge about the environmental conditions and required service life, certain limiting values for concrete cover and penetrability (of corrosive agents) can be specified. Once these limiting values on the as built structure meet the specified requirements, the structure is considered to be inherently durable (Alexander, 2007). However, a clear design methodology or guidelines for concrete structures that do not meet the specified minimum requirements needs to be established. Presently, no such guidelines exist owing to the lack of knowledge on the deterioration prevention mechanisms of various repair materials and systems and especially the durability of the repair system itself.

In earlier times, repair materials were relatively simple, but since the 1960's, an abundance of new materials and systems have been available for use. Of particular interest in this project is the use and durability of concrete coatings that can be used to increase the service life of concrete structures that do not meet specified durability requirements.

1.3 Dissertation structure

This work explores six generic type protective coatings used in the construction industry to provide protection against the ingress of deleterious agents. A number of other protective surface treatments are available for use however the products evaluated in this work were based on current prevalence amongst practitioners. In order to understand the need for protective products, it is important to understand the corrosion mechanisms of reinforced concrete structures. Thus, primary focus is given to corrosion caused by the ingress of carbon dioxide and chloride ions.

This work initially discusses the deterioration (and influencing factors) of reinforced concrete structures caused by carbonation and chloride ion induced corrosion. Since deleterious agents migrate through concrete in different ways it is important to understand what protection mechanisms are required by surface treatments.

Taking the discussion of corrosion further, this work explores the South African durability index approach by looking at the influence of corrosion on service life. The South African durability approach aims at quantifying service life based on the exposure conditions and concrete quality determined by laboratory testing. This work is therefore aimed at concrete failing to meet durability requirements and the potential service life improvement offered with the use of surface treatments.

A review of surface treatments, their composition and protection mechanisms are discussed in relation to carbonation and chloride ion induced corrosion. Some case studies and potential uses of surface treatments are discussed in order to understand both the positive aspects and potential failings of surface treatments. The knowledge gained from exploring corrosion mechanisms, protection mechanisms of coatings and previous research into concrete coatings was used to formulate a methodology to evaluate the protective properties and durability of coatings themselves.

After a review of the literature, it has been recognised that a clear approach for the introduction of protective coatings in the design and specification of reinforced concrete structures is presently missing. Currently, there is no such design approach that actively incorporates the effective service life afforded by a coating into the service life prediction of concrete structures. Results of this work suggest that surface treatments can be used effectively to prevent the onset of corrosion in concrete failing to meet durability requirements however it is recommended that further work is carried out to further incorporate the use of surface treatments into design specifications.

1.4 Aims and objectives

Concrete produced for construction needs to meet certain criteria in order to meet service life requirements. In the past, strength has been used as indicator of concrete quality and hence durability. Under the South African durability index approach, concrete is required to meet certain minimum requirements in order for it to be considered inherently durable under prescribed exposure conditions. However, when concrete fails to meet certain limiting values, concrete will not meet service life requirements unless mitigating steps are taken to prevent the ingress of deleterious agents.

Surface treatments can be applied to concrete to prevent the ingress of carbon dioxide and (or) chloride ions however, the effectiveness and longevity of commercially available products is largely unknown. In general terms, it was the aim of this work to assess the performance and durability of a number of different surface treatments in a battery of tests under various conditions. More specifically, using literature and an experimental project, this work aims to:

- Develop methods for assessing the durability of coatings for the application in various environments
- Produce poor quality concrete which would fail under the South African durability approach and require remedial action to fulfil service life requirements
- Apply surface treatments to concrete specimens and assess the performance of each product to prevent the ingress of carbon dioxide and (or) chloride ions after different periods of artificial weathering (0, 3, 6 and 9 years equivalent weathering)
- Assess physical characteristics of the surface treatments such as bond strength, layer thickness and penetration depth
- Use test data in conjunction with the South African durability approach to determine the effectiveness of surface treatments to extend the service life of concrete structures
- Establish an introduction to improve the performance based design methodology for reinforced concrete structures by incorporating coating systems into specifications for structures failing to meet durability requirements.

2 Literature review

2.1 Durability of concrete in aggressive environments

2.1.1 The permeability of concrete

Concrete is a porous and permeable material. Therefore, aggressive agents such as carbon dioxide and chloride ions in the form of gases and liquids may enter and migrate through concrete where depassivation of the reinforcing steel may occur. Corrosion can then begin if sufficient moisture is present in the concrete. The South African durability index approach defines the service life of reinforced concrete structures as the time taken for corrosion to initiate. In other words, the service life is the defined as the time taken for deleterious agents to migrate through the concrete cover to the depth of the reinforcing steel. Figure 3.1 illustrates the stages of corrosion given as a function of time and damage to the structure. This subject of service life is debatable and may include the propagation phase in many definitions. The durability of structures is primarily a function of permeability and the ease at which liquids and gasses are transported through concrete. Thus, the service life of a structure is heavily dependent on the permeability and the rate at which aggressive ions and molecules may enter and move through concrete (Richardson, 2002; Alexander et al 2008).

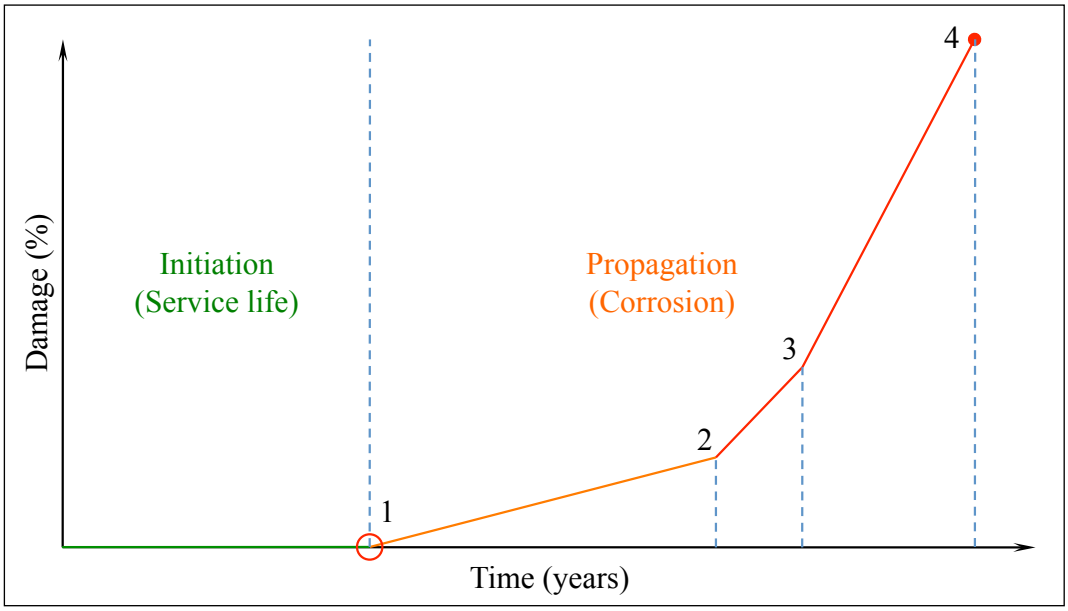

Figure 2.1: Service life and corrosion phases of reinforced concrete structures (Tuutti, 1982)

Table 2.1: Description of Figure 3.1 (Tuutti, 1982)

1. Depassivation of the reinforcing steel	Initiation period
2. Crack formation	Propagation period
3. Spalling concrete cover	
4. Eventual collapse of structure through bond failure or degradation of the cross section of the main reinforcement	

It is important to remember that porosity and permeability are two different properties of hardened concrete. The porosity describes the proportion of the material represented by voids while permeability is the capability of one material to pass through another. Concrete possesses both properties and is able to be both highly porous but relatively impermeable at the same time. Thus, one must take cognisance of the fact that although permeation requires a porous network, there is not always a direct link between porosity and permeability (Dhir et al, 1996; Richardson, 2002).

2.1.2 Factors affecting the permeability of concrete

Due to the fact that water is a constituent of concrete, pores will always exist in the paste and even high quality concrete will to some extent be permeable. The quality of the cement paste influences the permeability of concrete particularly around the aggregate (Dhir et al, 1996).

For differing agents, the permeability of concrete depends on the pore structure, the connectivity of the pores and the saturation state of the connected pores. The moisture content of the pores will vary according to the environment of the structure and can either be beneficial or detrimental to the durability of concrete. Pores that have high moisture contents will aid in the prevention of gasses migrating through the concrete but will assist in the migration of soluble ions. The relative size of the pores is larger than the ions and molecules migrating through the concrete. (Richardson, 2002).

In past years, compressive strength has been used as an indicator for concrete quality. This approach however has proved to be inadequate as it does not provide sufficient information regarding the cover concrete. As is the case with all reinforced concrete structures, cover concrete provides a physical barrier of protection for the embedded steel. All too often, poor quality concrete cover is responsible for the demise of reinforced concrete structures. Practitioners can however take precautions during the proportioning, mixing and placing of concrete to minimise the risk of premature failure caused by poor quality concrete cover. Nowadays, laboratory tests are used to estimate specific migratory properties of fluids through concrete such as permeability, sorptivity and diffusion. The inherent capillary pores and their associated interconnectivity of concrete are directly linked to the measured transport mechanisms. Concrete quality may therefore be improved through the reduction of capillary porosity, achievable with lowered water:cement ratios and increased degrees of hydration. The degree of hydration is directly affected by concrete curing, thus better curing techniques result in higher degrees of hydration. This concept is highlighted with the use of Figure 3.2 (Ballim and Basson, 2001).

In addition to the barrier protection provided by concrete cover, durability is affected by the amount of cementitious material available to chemically react with deleterious agents. In carbonating environments, durability is improved with increasing amounts of cementitious material and for this reason many codes of practice around the world specify minimum quantities of binder for concretes exposed to aggressive environments. Carbonation is one such process that is benefits from both decreased permeability and increased binder content. The movement of carbon dioxide is limited by decreased permeability while increased amounts of cementitious material is available to chemically react with the carbon dioxide (Ballim and Basson, 2001; Dhir et al, 1996; Kay, 1992).

Curing

Concrete curing is an important factor in durability considerations. Due to time and budgetary limitations, proper curing is often neglected. In all construction (but particularly were durability is a concern), it is recommended that concrete is cured for a minimum of 5 days at a temperature of 22°C (Ballim and Basson, 2001).

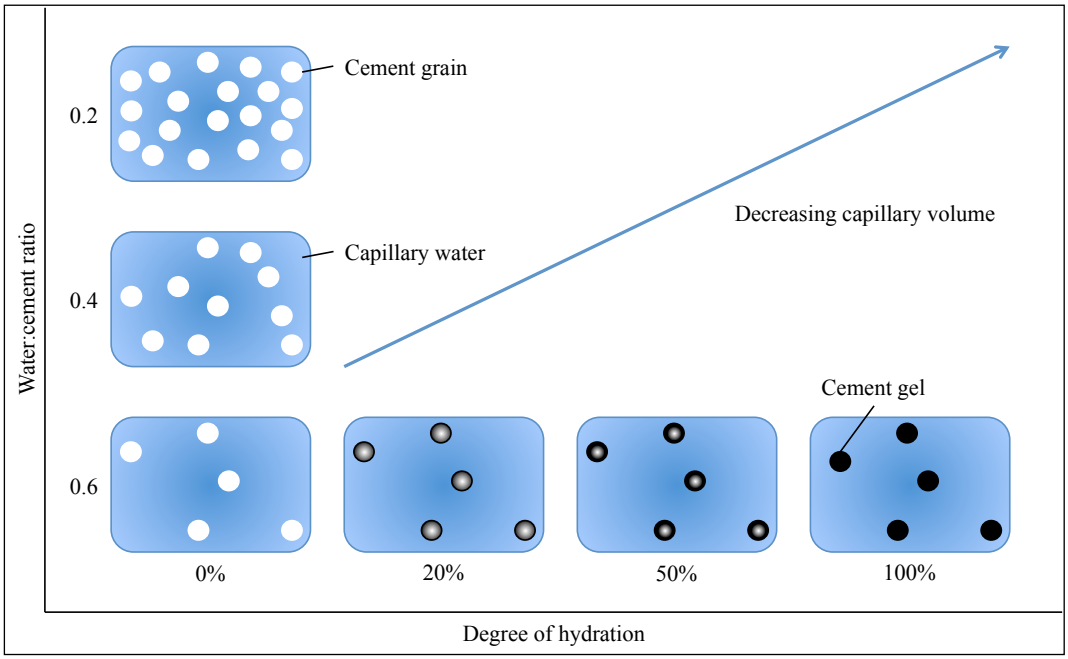

Figure 2.2: Effect of water:cement ratio and degree of hydration on capillary volume

The strength and durability of concrete are dependant on binder cementing reactions that take place during the curing period. Whether hydration or pozzolanic, the reactions must occur in the presence of water. Near surface concrete (cover concrete) provides barrier protection to embedded steel. Reduced permeability and hence increased durability characteristics are responsible for improving barrier protection of the cover concrete (Addis, 2001).

Binder type

Blended cements and cement extenders are commonly used in the production of concrete. They are often chosen because they provide concrete with desired properties that are lacking in plain cement mixes such as reduced permeability and reduced curing temperatures.

Fly ash

Permeability and capillary pores are reduced in concretes produced with fly ash mixes replacing up to 30% Portland cement. The reduction in permeability is accredited to the fineness of fly ash particles as well as the reduced water demand and the pozzolanic reaction in fly ash mixes. However, the carbonation resistance may be reduced with the addition of fly ash. Thus, the addition of fly ash may have undesirable effects in carbonating environments (Ballim and Basson, 2001).

Ground granulated blast furnace slag (GGBS)

There is little difference in the porosity values for plain cement and GGBS concretes cured for 28 days with the same water:binder ratio. The difference lies in the make up of the total porosity. GGBS mixes contain more gel pores and fewer capillary pores. In terms of the migration properties of deleterious agents through concrete, GGBS mixes provide little benefit over plain cement mixes. The crucial difference lies in the chloride binding ability of GGBS which is able to delay the possible onset of corrosion. It should be noted however that higher carbonation rates may be observed in GGBS concretes (Ballim and Basson, 2001).

Condensed silica fume (CSF)

Concretes produced with CSF possess good chemical resistance and benefit from reduced permeability and porosity. These beneficial characteristics are accredited to the fineness and the high pozzolanic reactivity of the material. It has been shown that CSF concretes reduce oxygen permeability, water sorptivity and chloride conductivity while increasing strength (Ballim and Basson, 2001).

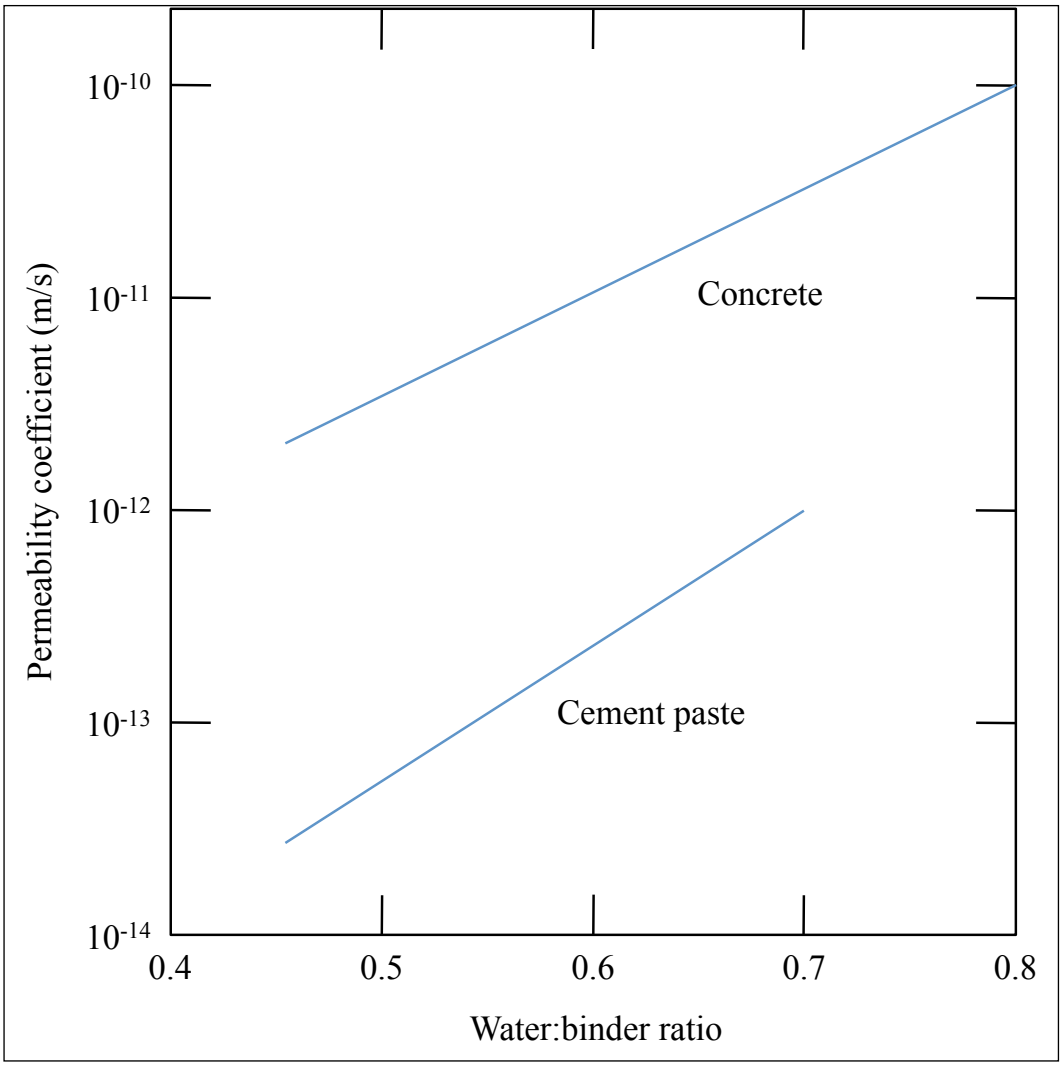

Figure 2.3: Influence of water:binder ratio on concrete permeability (Ballim and Basson, 2001)

Water:binder ratio

Concrete permeability is primarily affected by the water:binder ratio. Due to the importance of the water:binder ratio as an indicator for permeability, it is often used as a specification for concretes exposed to aggressive environments. Figure 3.3 links the water:binder ratio as an indicator to the permeability coefficient of hardened concrete and cement paste (Bader, 2003; Ballim and Basson, 2001).

2.2 The corrosion of reinforced concrete structures

2.2.1 Influence of the hydration reaction on corrosion

The cementing or binding component of concrete can be 100 percent ordinary Portland cement or combined in a number of ways with supplementary cementitious materials such as ground granulated blast furnace slag, corex slag, fly ash and condensed silica fume. The choice and combination of these materials will depend on the required properties of the concrete mix. These so called binding agents are blended and when mixed with water, they begin to chemically react (through a hydration process). The macroscopic result of the hydration reaction is a hard cement matrix (paste) that is able to lock the aggregates in place. Microscopically, the process is complicated and a discussion is needed so that the hydration process is understood In keeping with the convention used by concrete practitioners, the following abbreviations shall be used to describe the hydration process (Addis, 2001):

C = Calcium oxide (CaO)
S = Silica (SiO_2)
A = Alumina (Al_2O_3)
F = Ferric oxide (Fe_2O_3)
H = Water (H_2O)

Thus;

C_3S = Tricalcium silicate
C_2S = Dicalcium silicate
C_3A = Tricalcium aluminate
C_4AF = Tetracalcium aluminoferrite
CH = Calcium hydroxide ($Ca(OH)_2$)

For Portland cement, the hydration reaction occurs in the following steps:

$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$ (1)
$2C_2S + 4H \rightarrow C_3S_2H_3 + CH$ (2)
$C_3A + CH + 12H \rightarrow C_4AH_{13}$ (3)
$C_4AF + 4CH + 22H \rightarrow C_4AH_{13} + C_4FH_{13}$ (4)

The above reactions are all exothermic, heat is therefore released and concrete becomes noticeably warmer during this reaction. The calcium hydroxide for reaction (3) and (4) is provided from the first two reactions (Addis, 2001).

It must at this point be noted that the calcium hydroxide (CH) formed in the above hydration reaction is responsible for reacting with carbon dioxide during carbonation. The carbonation process will be discussed later, but for the time being, it is accepted that the reaction between calcium hydroxide and carbon dioxide produces calcium carbonate. A reduction of the alkalinity of the concrete is associated with the formation of calcium carbonate, which in turn causes depassivation of the reinforcing steel to occur. Once depassivation of the reinforcing steel occurs, the corrosion process can proceed (Ballim and Basson, 2001).

Concrete provides an inherently safe environment for reinforcing steel such that corrosion will not occur. The hydration reaction of Portland cement produces calcium hydroxide which is primarily responsible for the high alkalinity of the pore water (pH > 12.5). When exposed to the highly alkaline pore solution in concrete, a passive, gamma ferric oxide layer will form on the surface of the reinforcing steel. While high alkalinity is maintained, this layer remains intact and corrosion will not occur. Concrete however is a porous material and deleterious substances may be able to enter the concrete and depassify the reinforcing steel by reducing the alkalinity. Once the gamma ferric oxide layer has been destroyed on the surface of the reinforcing steel, corrosion is able to begin provided water and oxygen are present. (Ballim and Basson, 2001; Kay, 1992)

2.2.2 The corrosion mechanism of reinforcing steel

Corrosion is a two-part electrochemical process consisting of anodic and cathodic reactions. The process is the same for concretes that have undergone carbonation or suffered from chloride ingress. The reaction is able to begin once the passive layer on the steel has been destroyed by the reduced pH of the concrete either through carbonation or chloride ion attack (Hunkeler, 2005). When corrosion begins, areas of hydrated ferric oxide (rust) will start to appear on the steel surface. Corroding steel in concrete dissolves in the pore water and releases electrons. This is the anodic reaction (occurring at the anode) and is given by (Broomfield, 1997; Ballim and Basson, 2001):

$$Fe \rightarrow Fe + 2e^-$$

In the anodic reaction, two electrons are released. To ensure that electrical neutrality is preserved in the system, these electrons must be consumed at the cathode. This prevents large amounts of charge from building up in the system. The cathodic part of the electrochemical reaction will occur at the cathode as is given by (Broomfield, 1997; Ballim and Basson, 2001):

$$2e^- + H_2O + \tfrac{1}{2}O_2 \rightarrow 2OH^-$$

Hydroxyl ions ($2OH^-$) are generated at the cathode. Hydroxyl ions are highly basic and tend to increase the alkalinity in the area surrounding the cathode and aids in building up the passive layer around the steel. This therefore increases the resistance of the steel against carbonation and chloride ion attack at the cathode (Broomfield, 1997). From the cathodic reaction, it is important to note that oxygen is the driving force and must be present in sufficient amounts at the concrete-steel interface for the corrosion to proceed (Hunkeler, 2005).

The anodic and cathodic reactions given above are only the first steps in the formation of rust. For the anodic and cathodic reactions to proceed, there needs to be a flow of ions between the site of the anode and the site

of the cathode. For ions to flow, a suitable electrolyte must exist, which in concrete, is present in the form of pore water. Another important condition for the anodic and cathodic reactions to proceed is the flow of electrons. In a monolithic reinforced concrete member, a metallic connection between the anodic and cathodic sites exists in the form of reinforcing steel such that electrons can flow from the anode to the cathode (Hunkeler, 2005). The damage caused to concrete (cracking and spalling) is not due to the dissolution of the iron ions into the pore water. Several more reactions are required for the formation of rust. The equations for the formation of rust are given below (Biczók, 1972; Broomfield, 1997):

$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$

In the above reaction, the dissolved iron ions react with the hydroxyl ions to form ferrous hydroxide. The ferrous hydroxide now reacts with water and oxygen to form ferric hydroxide given by (Broomfield, 1997):

$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$

In the final step, the formation of hydrated ferric oxide (rust) is shown:

$2Fe(OH)_3 \rightarrow Fe_2O_3.H_2O + 2H_2O$

Unhydrated ferric oxide (Fe_2O_3) is volumetrically twice as large as the parent steel from which it comes. Depending on the degree of hydration, hydrated ferric oxide ($Fe_2O_3.H_2O$) can occupy up to ten times the volume of the original parent steel because it swells and becomes porous. Cracking and spalling of the concrete may occur if the tensile capacity of the concrete is exceeded as expansion and swelling of the rust occurs. The process is illustrated in Figure 3.4 (Broomfield, 1997):

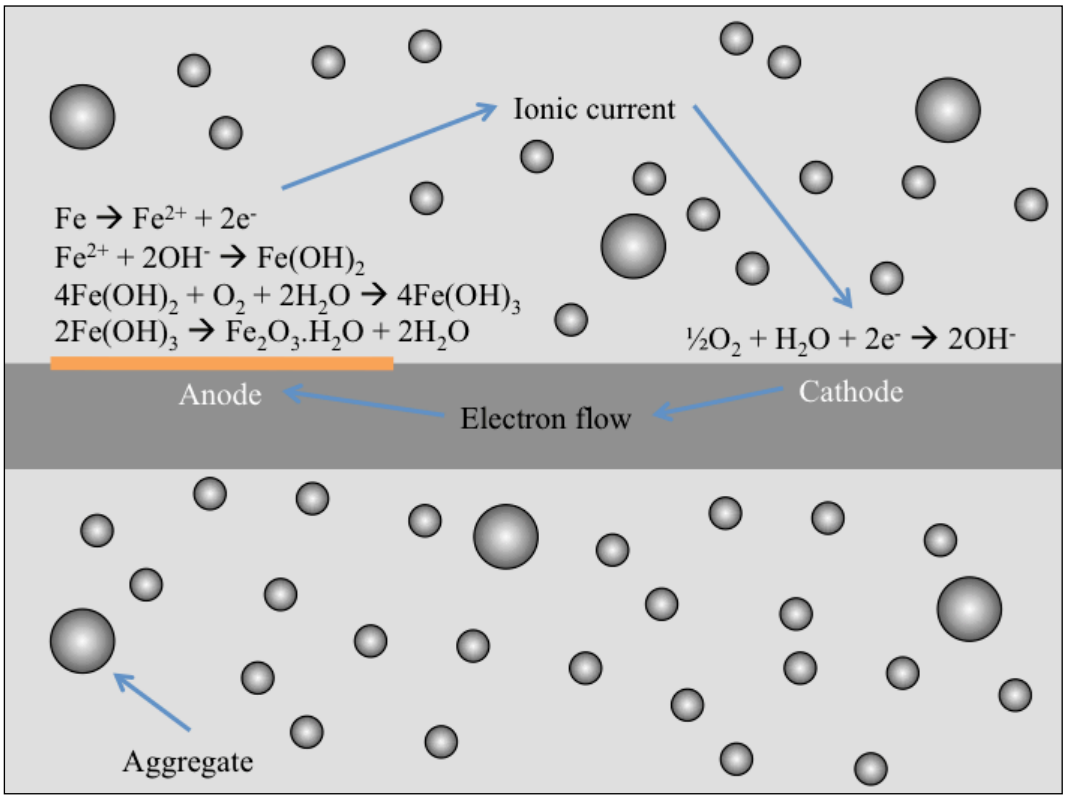

Figure 2.4: Corrosion and the formation of rust (Broomfield, 1997)

The most significant causes of corrosion deterioration of reinforced concrete structures are carbonation and chloride ingress. Water, oxygen and aggressive agents will enter concrete structures to varying degrees depending on their location and exposure conditions. Once the protective passive layer on the reinforcing steel is destroyed by carbonation or chloride ingress, corrosion may proceed if water and oxygen are present. The expanding steel corrosion products cause visible staining, cracking of the concrete cover and eventual spalling. The effects of corrosion are widespread and can be seen in many concrete structures. The service life of concrete structures can to a large extent be reduced due to the affects of corroding steel if mitigating steps are not taken (Lees, 1992; Kay, 1992).

2.2.3 Chloride induced reinforcement corrosion

Chlorides may be available from external sources and migrate into concrete or to a lesser extent, they may be present when concrete is cast. They can be mixed into concrete for a number of intentional or accidental reasons including (Broomfield, 1997):

- Calcium chloride ($CaCl_2$) was used up until the 1970's as a concrete accelerator
- Seawater can be used as mixing water
- Aggregates (usually obtained from the sea bed) that are unwashed or poorly washed will contain chlorides that will be mixed into the concrete

Chloride ingress from external sources happens quickly through capillary action. Cyclic wetting and drying accelerates the movement of chlorides into hardened concrete. The result of ingress through capillary action is a deep chloride profile within the concrete. Chlorides are provided from the following sources (Hunkeler, 2005; Broomfield, 1997):

- Spray and wetting from sea water
- De-icing salts
- Chemicals

To a large extent, the work surrounding the topic of durable concrete structures has focused on the migration of chloride into concrete from external sources. Chlorides cast into concrete can be controlled under good site practice but should not be neglected from discussion, as they are as much a part of the problem as chlorides from external sources. Even at very low levels, cast-in chlorides can accelerate the inception of corrosion as more chlorides become available from external sources. Concrete found in marine environments is often subject to accidental contamination from seawater in the casting stage. As chlorides from the seawater diffuse through the hardened concrete, they combine with the cast-in chlorides to accelerate the initiation phase of corrosion (Broomfield, 1997).

Chloride penetration has the same effect as carbonation on attacking the passive protective layer surrounding the steel in reinforced concrete. However, the depassivation mechanism for chloride penetration is quite different from carbonation. Chloride ions entering concrete attack the passive protective layer surrounding the reinforcing steel, but there is no reduction in alkalinity of the surrounding concrete. When the chloride content at the surface of the reinforcing steel is high enough, they are able to break down the passive layer and act as a catalyst for the corrosion process. In other words, chlorides do not actively take part in the corrosion process but rather; they speed up the process by depassifying the reinforcing steel. Once the

passive oxide layer on the steel begins to break down, mitigation is often ineffective because the removal of chlorides is difficult (Broomfield, 1997; Kay, 1992).

As chlorides enter concrete, a portion will bind to the cement matrix (predominantly to the aluminates) and thus will not be available to migrate further. The binding capacity of concrete is primarily related to the chemical composition of the cement type and other additives. The binding capability of the cement paste however is not permanent and chlorides may be released at a later stage if the pH of the concrete is lowered due to carbonation. Thus, only mobile chlorides will be available to migrate through concrete down to the reinforcing steel (Bader, 2003; Hunkeler, 2005).

Minimum chloride content

For chlorides to effectively destroy the passive oxide layer on reinforcing steel, a minimum concentration must exist. Reinforcing steel has the ability to regenerate its passive oxide layer in low concentrations of chlorides. Corrosion in low concentrations of chlorides will thus not occur. It is widely accepted that the chloride content must exceed some limiting value at the surface of the steel for corrosion to commence. The threshold for corrosion has been defined in terms of a chloride to hydroxyl ratio and an equivalent chloride by mass cement percentage. In earlier work, it was suggested that the threshold ratio of chloride to hydroxyl should be taken as 0.6, which equates to a 0.4% chloride content by mass of cement (Broomfield, 1997). However, due to the reasons discussed below, these values should not be used as an indication for all concretes (Hunkeler, 2005).

It is difficult to define a certain chloride content or chloride to hydroxyl ratio to initiate corrosion because the alkalinity of concrete largely depends in the composition and the degree of carbonation in the cover. A relatively small change in the pH of concrete represents a large change in the hydroxyl ion (OH^-) content which in turn will have a large effect of the chloride to hydroxyl ratio (Broomfield, 1997).

Chlorides may be temporarily or permanently bound in the framework of the cement paste. This can either occur chemically when chlorides attach to the aluminates in the cement paste or physically when chlorides are absorbed into the pores walls. Chemically, chlorides will react with tricalcium silicate (C_3A) to form chloroaluminate, which is insoluble in pore water and non-reactive. High concentrations of tricalcium silicate in the cement will react with more chlorides entering concrete. When sulphates and chlorides are available, they will both react with tricalcium silicate to form sulfoaluminates and chloroaluminates respectively. However, sulphates are more reactive and will tend to react in preference to chlorides. If chlorides become bound, they are not able to migrate further into the concrete and will not be available to initiate corrosion by breaking down the passive oxide layer on the reinforcing steel. In concrete produced from sulphate resisting cement, chloride diffusion is rapid and the chloride threshold is reduced because of the low aluminate content. In carbonated concrete, chlorides are once again released when the chloroaluminate is carbonated. Chlorides that were once bound in the cement framework are released, become mobile and are able to travel further into the uncarbonated concrete (Lees, 1992).

Chlorides will diffuse through concrete via the capillary pores. The rate of diffusion will depend on the fineness and tortuosity of the pore structure. In some environments, a chloride concentration gradient may exist and chlorides will migrate from areas of high to areas of low chloride concentrations. Thus depending on the concentration gradient, chlorides may either enter or leave concrete. For concrete in the marine

environment, chlorides will continually react with tricalcium aluminate and cause the ingress of more chlorides as a concentration gradient develops. However, practical experience has shown that chlorides diffuse very slowly through concrete and a more effective transport mechanism is through cyclic wetting and drying (Lees, 1992).

Depth of chloride ingress and time relationship

Fick's second law is usually used to describe the time and depth of chloride ingress. Many models have been developed over the years that try to explain movement of chloride ions through concrete. Chloride profiles are calculated as a function of time and surface chloride concentration. The equation is given below (Hunkeler, 2005):

$$c(x,\ t)\ =\ c_s\left[1-\text{erfc}\left(\frac{x}{2\sqrt{D_{eff}\cdot t}}\right)\right]$$

Where: $c(x, t)$ = chloride content at depth x and time t (% chlorides by mass of binder)
erfc = error function
D_{eff} = effective chloride diffusion coefficient (m^2/s)
c_s = surface or near surface chloride content (% chlorides by mass of binder)
x = depth (m)
t = time (s)

It should be noted that the chloride coefficient is not constant but rather it varies with time (age), pore structure (depth) and environmental conditions (moisture content) of the concrete. Furthermore, it must be noted that the above model assumes that the movement of chloride ions is by diffusion only. This however is not the case because the movement of chloride ions is not a pure diffusion process. In practice, the model gives relatively rough figures that can be used to design reinforced concrete structures (Hunkeler, 2005).

2.2.4 Carbonation induced reinforcement corrosion

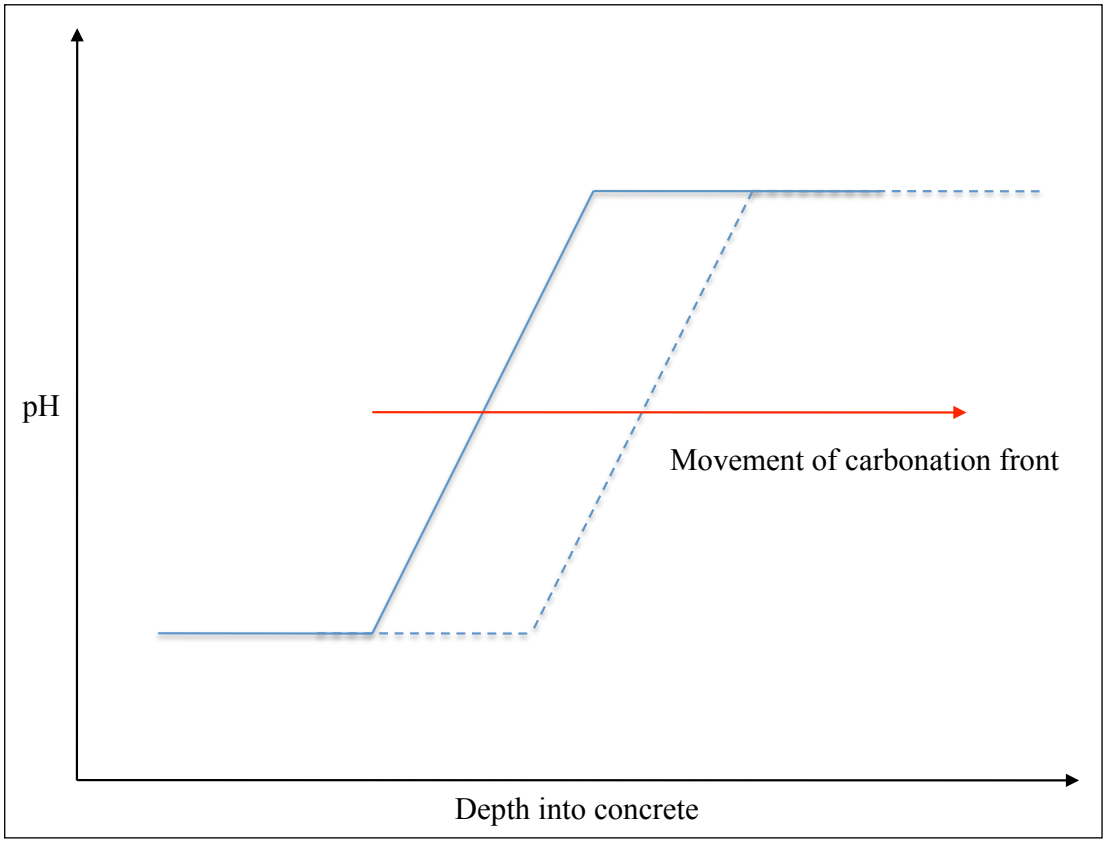

Figure 2.5: The carbonation front (Ballim and Basson, 2001)

The alkalinity of concrete is reduced when carbon dioxide from the atmosphere dissolves in pore water to form an acidic solution that reacts with the alkaline constituents of the cement paste. (Biczók, 1972; Hunkeler, 2005). The acidic solution will neutralise the alkaline environment of the concrete. In other words, the pH of the concrete (initially greater that 12.5) will start to drop (to values between 6 and 9) as the acidic solution neutralises the alkaline environment (Lees, 1992). Carbonation is defined as the process in which an acidic solution neutralises the alkalinity of concrete (Biczók, 1972). As the process of carbonation continues, acidic pore water migrates further and continues to lower the pH of the concrete. Carbonation is referred to as a front that passes through a concrete body. A visual interpretation of the carbonation front is presented in Figure 3.5 (Ballim and Basson, 2001).

When the carbonation front eventually reaches the reinforcing steel, the pH of the concrete surrounding the steel is lowered. The passive film that prevents reinforcing steel against corrosion is able to provide protection as long as the pH of the concrete remains above 11. Thus, the carbonation front is responsible for the destruction of the protective passive layer on the reinforcing steel. Once the passive layer has been destroyed, corrosion can proceed provided water and oxygen are present in sufficient quantities (Hunkeler, 2005).

Chemical changes associated with carbonation

As mentioned, carbonation occurs because an acidic pore water solution of carbon dioxide reacts with the alkaline components of the cement paste. The process of carbonation is not a simple one, and a discussion of the associated chemical changes and reactions is needed. Carbon dioxide gas in the atmosphere reacts with hydroxides to form carbonates. Carbonic acid is formed when carbon dioxide enters concrete and dissolves in the pore water (Hunkeler, 2005; Lees, 1992):

$CO_2 + H_2O \rightarrow 2H^+ + CO_3^{2-}$

The alkaline constituents of the cement paste dissociate in the pore water according to the following reactions:

$NaOH \rightarrow Na^+ + OH^-$
$KOH \rightarrow K^+ + OH^-$
$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$

The reactions above only represent the dissociation of the ions in water. The full reaction of the alkaline components with water and carbon dioxide in which water is released is provided below:

$2NaOH + 2H_2O + CO_2 \rightarrow Na_2CO_3 + 2H_2O$
$2KOH + H_2O + CO_2 \rightarrow K_2CO_3 + 2H_2O$
$Ca(OH)_2 + H_2O + CO_2 \rightarrow CaCO_3 + 2H_2O$

The products of sodium carbonate (Na_2CO_3) and potassium carbonate (K_2CO_3) are more soluble than calcium carbonate ($CaCO_3$). This means that calcium carbonate is deposited; where as the carbonates of sodium and potassium remain in solution. If water and carbon dioxide is still available, then the above carbonates will further react to form soluble hydrogencarbonates (denoted by the HCO_3) part of the products). The formation of hydrogencarbonates causes a further reduction of the pH of the concrete (Hunkeler, 2005):

$Na_2CO_3 + H_2O + CO_2 \rightarrow 2NaHCO_3$
$K_2CO_3 + H_2O + CO_2 \rightarrow 2KHCO_3$
$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$

Carbon dioxide contained in the atmosphere is in direct contact with the outer surface of a concrete member and will enter the near surface capillary pores. Once in the pores, the carbon dioxide is used up quickly as it reacts with the hydroxides of sodium, potassium and calcium. The air becomes decarbonated which causes a concentration difference to occur between the atmosphere and the air in the near surface capillary pores. Carbon dioxide from the atmosphere will now tend to move towards the decarbonated air in the concrete to restore the state of homogeneous concentration in a process called diffusion (Lees, 1992).

As more carbon dioxide enters the concrete, it is used up quickly as it reacts with the hydroxides. A definite line between the carbonated and uncarbonated concrete usually exists because carbon dioxide will not move further into the concrete until all the hydroxides have reacted. Only when all the hydroxides of sodium,

potassium and carbon have been converted into their respective carbonates, carbon dioxide will begin to move into the uncarbonated concrete (Lees, 1992). This phenomenon can be observed in the form of a carbonation front, which can be seen in Figure 3.5 (Ballim and Basson, 2001).

In air that contains 0.03% and 1% carbon dioxide, the pH of the reaction between calcium carbonate, water and carbon dioxide will be in the region of 8.5 and 7 respectively. In atmospheres of pure carbon dioxide, a pH of 6 will be produced by the same reaction. The reactions between the carbonates of sodium and potassium with water and carbon dioxide will produce values one pH unit higher than the reaction of calcium carbonate, water and oxygen (Hunkeler, 2005).

As carbon dioxide continues to enter concrete, it reacts with and reduces the calcium hydroxide. The calcium silicate hydrate gel (responsible for the cement paste strength) becomes less stable under the condition of depleted calcium hydroxide and begins to decompose to release more calcium hydroxide. This process leaves behind an irregular lattice of hydrated silica. Other hydrates from the cement paste behave in a similar fashion leaving behind a network of silica, alumina and iron oxide filled with calcium carbonate. The irregular structure left behind in the carbonated layer of concrete is both stronger and more resistant to the migration of carbon dioxide than uncarbonated concrete. Thus, the above relationship exists because as the depth of carbonation increases, new carbon dioxide entering the concrete must travel further and through less permeable concrete (Lees, 1992).

The water content of concrete will affect carbonation in two ways. Concrete can either be too wet or too dry. In each of these conditions, carbonation will occur at a decreased rate than in damp concrete. If calcium hydroxide is dry, it reacts very slowly with carbon dioxide. The rate of this reaction now becomes the governing condition for rate of carbonation. In an optimally damp condition, calcium hydroxide is coated with a thin surface layer of moisture, this ensures that the reaction between calcium hydroxide and carbon dioxide is more complete and occurs at an increased rate. In saturated concrete, carbon dioxide must diffuse through the pore structure that is completely filled with water. Diffusion now occurs at a much slower rate because the concrete is saturated. The diffusion rate now becomes the governing condition for the rate of carbonation (Lees, 1992).

The formation of an acidic solution and subsequent reactions of other gases such as sulphur dioxide (SO_2) and nitric oxides (NO_x) will have the same effect on neutralization that carbon dioxide has. Their affect is negligible however because the atmospheric concentrations of these gases is much lower than carbon dioxide (Hunkeler, 2005).

The depth of carbonation and time relationship

Based on Fick's first law of diffusion, a simple equation for the time dependency for carbonation was established in the 1960's (Hunkeler, 2005):

$$x = \sqrt{\frac{2D}{a}\left(c_1 - c_2\right)} \cdot \sqrt{t} = A\sqrt{t}$$

Where: x = depth of carbonation at time t (m)
D = diffusion coefficient of carbon dioxide in carbonated concrete (m^2/s)
a = carbon dioxide required for the carbonation of the alkaline constituents (g/m^3)
c_1 = concentration of the carbon dioxide in the surrounding air (g/m^3)
c_2 = concentration of the carbon dioxide in the carbonation front (g/m^3)
t = time (s)
A = carbonation constant

Several assumptions have been made in the derivation of the above equation. The assumptions will only hold for idealised or constant conditions normally found indoors. Natural or outdoor conditions do not fulfil the requirements for the model because factors such as rain are not considered. It is found that in outdoor conditions, the rate of carbonation decreases continually until an ultimate value for carbonation is reached. Thus the above model will tend to overestimate carbonation to a certain extent for natural weather conditions. This could lead to unnecessary and expensive design or rehabilitation measures for concrete structures (Hunkeler, 2005).

A second model was developed in the 1970's that accounted for the moisture content of concrete and the associated influence on the diffusion coefficient of carbon dioxide. In this modified model, it can be seen that an ultimate or final carbonation depth is eventually reached. This is more accurate and simulates outdoor conditions better than the original model (Hunkeler, 2005):

$$t = -\frac{a}{b}\left[x - x_\infty \ln\left(1 - \frac{x}{x_\infty}\right)\right]$$

Where: x = depth of carbonation after time t (m)
x_∞ = final carbonation depth (m)
a = carbon dioxide required for the carbonation of the alkaline constituents (g/m^3)
b = constant depending on the moisture content
t = time (s)

Cracking due to carbonation

Finally, if the carbonation front has reached the reinforcing steel, then corrosion may begin provided water and oxygen are present. The corrosion products of steel are volumetrically larger than the parent material. The concrete member will begin to crack and spalling may occur because tensile stresses are introduced due to the increased volume occupied by the corrosion products.

As corrosion continues, mass is lost from the steel rebar and the crack widths (induced by the expanding corrosion products) begin to increase. The corrosion risk according to the carbonation depth to cover thickness ratio, increases as this ratio increases (Hunkeler, 2005).

2.3 South African durability index approach

In the early 1990's, a research project was started that was to improve the quality of reinforced concrete construction in South Africa. Particular attention was given to the premature corrosion of reinforcing steel caused by the ingress of harmful agents. In order for limiting values to be imposed on concrete quality, it was important that the materials used in construction were characterised. Furthermore, relevant test methods and models were developed. Recently, these limiting values have been adopted into the specification of structural concrete in much the same way strength is specified (Alexander et al, 2007). In past years, strength has been the main design criterion for concrete structures. Similar strength concrete can be achieved through a range of different mix designs, proportioning and curing conditions. Durability on the other hand is widely affected by different mix designs, proportioning, placing and curing conditions. Therefore, it is recognised that strength is an important design parameter however durability is also an important design consideration of reinforced concrete. Furthermore, long-term maintenance costs are greatly reduced through the use of good quality concrete (Alexander and du Preez, 2004; Alexander et al, 2008).

Three such limiting values can be specified and used to classify concrete: Oxygen permeability, water sorptivity index and chloride conductivity. Currently, only the oxygen permeability index and chloride conductivity index are used to describe relevant transport mechanisms in concrete. To date, water sorptivity although tested in the laboratory is not used as indication of concrete quality as is not linked directly to concrete deterioration (Alexander, 2007). The advantage of using concrete durability indices is that test methods provide quantitative results. The results can then be used to classify or categorise concrete durability (Alexander et al, 2008). Some details of the tests methods have been discussed in Chapter 4 - Experimental work, however, further details can be found in *research monograph no. 4* (Alexander et al, 1999).

2.3.1 Performance indicators

Just as structures are custom built to fulfil specific roles, the same philosophy must apply to the durability of structures. Just as structures behave differently under different loading conditions, different environmental conditions will ultimately determine the longevity of reinforced concrete structures. It is thus important that the durability of concrete structures be related to the environmental exposure conditions. The durability of concrete is not only determined by the environmental conditions, but also by the properties of the concrete. In other words, durability of reinforced concrete structures is related to both intrinsic concrete (quality and cover depth) properties and extrinsic (climatic and exposure) conditions. It is important that these properties and conditions are well established before limiting durability index values are specified (Alexander, 2007).

It is important at this stage to realize that as with strength, one must differentiate between the material potential and the as built quality. Under ideal conditions, the durability of concrete can potentially be greater than the durability of an as built structure. However, the quality of as built concrete is both a function of material potential and workmanship. Both of these factors must be accounted for during the design stage, as well as the specification of limiting durability indices. When discussing the quality of concrete, one must be mindful of the fact that quality can describe both strength and durability. The surface concrete of reinforced concrete structures is the layer through which harmful agents will migrate and lead to the eventual corrosion of the reinforcing steel. The inner portion of the concrete is primarily responsible for the strength. The ability of the near surface concrete to resist the movement of is largely affected by construction methods and workmanship. Thus, potentially durable concrete may yield less than satisfactory durability parameters if placement and workmanship is not performed to rigorous standards (Alexander et al, 2007).

Presently, work is under way to calibrate durability indices obtained from short-term laboratory tests with structures that have been naturally exposed for extended lengths of time. Ultimately, if durability indices relate to long-term test data then the South African durability index approach can potentially be used for the control of concrete cover quality (Alexander et al, 2008).

2.3.2 Exposure conditions

The exposure conditions for the South African Durability Approach have been based on modified EN206 exposure conditions. Corrosion can occur once sufficient carbonation or chloride ingress has occurred. Therefore, pertinent conditions have been identified and are presented in Tables 3.1 and 3.2 (Alexander et al, 2007):

Table 2.2: Natural environmental classes for carbonation induced corrosion (EN206)

Designation	Description
XC1	Permanently dry or permanently wet
XC2	Wet, rarely dry
XC3	Moderate humidity (60-80%) (Exterior concrete sheltered from rain)
XC4	Cyclic wet and dry

Table 2.3: Natural environmental classes for chloride induced corrosion from seawater (EN206)

Designation	Description
XS1	Exposed to airborne salt but not in direct contact with seawater
XS2a*	Permanently submerged
XS2b*	XS2a and exposed to abrasion
XS3a*	Tidal, splash and spray zones
XS3b*	XS3a and exposed to abrasion

**Sub-clauses are a deviation from EN206 and have been added for South African conditions*.

2.3.3 Service life

Categorization of structures and the associated service lives are presented in Table 3.3. The categories have been taken from EN 1990 and serve as a guide only, essentially the owner of the structure will decide on the service life (Alexander et al, 2007).

Table 2.4: Recommended service life for different structure types (EN1999)

Design Category	Indicative working life	Types of structures
1	10 years	Temporary
2	10 to 25 years	Replaceable structural parts
3	15 to 30 years	Agriculture and similar structures
4	50 years	Buildings and other common structures
5	100 years	Monumental building structures, bridges and other civil engineering structures

2.3.4 Cover depth and durability index values

Cover depth is described as the layer of concrete covering the reinforcing steel. In other words, it is the region of concrete between the as cast face and the reinforcing steel and primarily responsible for the protection of the steel reinforcing. Usually, the thickness of concrete cover ranges between 25 and 80 mm. It must be noted at this point that the designer stipulates the cover depth but minimum values are normally 30 and 50 mm for carbonating and marine conditions respectively. Cover depth however, is not the only parameter specified by designers and should be used in conjunction with limiting durability indices. One must bear in mind that a balance exists between concrete quality and cover depth. In other words, if concrete quality is high (according to the durability index test results) than one may opt for less cover. If on the other hand, concrete quality is deemed to be poor then the designer must specify more cover (Alexander and du Preez 2004; Alexander, 2007).

At this point, the engineer is faced with a choice. He or she can either specify limiting durability values based on a deemed-to-satisfy approach or by way of a rigorous approach. Usually, durability indices can be prescribed according to the deemed-to-satisfy approach, but where the assumptions made in the deemed-to-satisfy approach are no longer adequate, the rigorous approach should be considered (Alexander et al, 2007). Clarification of the approaches is made possible from the ensuing discussion.

2.3.5 Deemed-to-satisfy approach

With guidance from a service life models, the engineer is able to prescribe limiting durability index values. This approach is similar to following a code of practice in the design phase and certain limiting values have been provided for general conditions of exposure. The majority of the work surrounding the South African durability index approach has been performed with structures and materials from the Western Cape (Alexander et al, 2007).

Carbonation

In the South African durability approach, the carbonation resistance of concrete has been closely linked to the 28 day oxygen permeability test result. From Table 3.5, it is necessary to specify oxygen permeability values for XC3 and XC4 exposure conditions. It is noted that XC4 is the more critical exposure class for the carbonation of concrete. Furthermore, carbonation of concrete in XC1 and XC2 exposure conditions should not occur provided the concrete cover is greater than 30mm (Alexander et al, 2007).

For carbonation protection, 50 and 100 year service life structures are considered. These two structure types are presented with the associated minimum cover depth and oxygen permeability values in Table 6.4. For 100 year structures, the designer has two options for specifying cover depths and corresponding oxygen permeability values.

Table 2.5: Deemed-to-satisfy values for carbonating concrete

	Common structures (50 year service life)	**Monumental structures (100 year service life)**	
		Option 1	**Option 2**
Service life	50	100	100
Minimum cover	30mm	30mm	40mm
Minimum OPI*	9.70	9.90	9.70

**This is the OPI value that must be achieved in the as-built structure after 28 days.*

Chloride attack

The chloride resistance of concrete has been linked to the chloride conductivity measured in the laboratory. Therefore, the chloride conductivity index can be used to specify minimum requirements for concrete in the marine environment. It has been prescribed that the minimum concrete cover for protection against the ingress of chlorides should be 50 mm for both 50 and 100 year design lives. Maximum chloride conductivity values for various binder types are presented in Tables 3.5 and 3.6 for 50 and 100 year design lives respectively. It is important to note that chloride conductivity is heavily dependent on the binder type and it has been recommended that only blended cements are to be used in the marine environment as singular use of CEM I in concrete provides insufficient protection against chloride ingress. Furthermore, it is recommended that the maximum water:binder ratio to be used in marine conditions should be no more than 0.55. The deemed-to-satisfy approach may conditionally accept higher water:binder ratios, but engineers should remain cautious (Alexander et al, 2007).

In Tables 6.5 and 6.6: *Fly ash = type F*
GGBS = Ground granulated blast furnace slag
GGCS = Ground granulated corex slag
CSF = Condensed silica fume

Table 2.6: Maximum chloride conductivity values* (mS/cm) for different classes and binder types (50 year design life)

Exposure class	70:30 CEM I:Fly ash	50:50 CEM I:GGBS	50:50 CEM I:GGCS	90:10 CEM I:CSF
XS1	3.00	3.50	4.00	1.20
XS2a	2.45	2.60	3.25	0.85
XS2b, XS3a	1.35	1.60	1.95	0.45
XS3b	1.10	1.25	1.55	0.35

**Maximum values obtained from 28 day samples taken from the as built structure.*

Table 2.7: Maximum chloride conductivity values* (mS/cm) for different classes and binder types (100 year design life)

Exposure class	70:30 CEM I:Fly ash	50:50 CEM I:GGBS	50:50 CEM I:GGCS	90:10 CEM I:CSF
XS1	2.50	2.80	3.50	0.80
XS2a	2.15	2.30	2.90	0.50
XS2b, XS3a	1.10	1.35	1.60	0.35
XS3b	0.90	1.05	1.30	0.25

**Maximum values obtained from 28 day samples taken from the as built structure.*

2.3.6 Rigorous approach

The rigorous approach is not as simplistic as the deemed-to-satisfy approach. It is more complex and requires the use of service life models developed as part of the South African durability approach. Engineers and designers are able to use specific values properties in the service life models such as cover depth, environmental classification, service life and material type to obtain specific limiting values for a given project. Clearly, the engineer is able to obtain more relevant limiting values using this approach because the generic classes can be avoided. Good knowledge of the models is required to safeguard against misinterpretation of the results (Alexander et al, 2008).

2.3.7 Accountability

Ensuring good quality concrete is dependent on material properties and good site practice. If limiting durability requirements of as built structures are met, then the structure is considered to be durable and will last fulfil the required service life requirements. However, when limiting durability values are not met, the as built structure may not be likely to fulfil the service life requirements. In this case, the responsible party or parties must mitigate the effects. Because the durability is affected by material properties and site practice, a two tier testing system has been set in place so that durability indexes for as delivered and as built concrete may be determined (Alexander et al, 2007).

To determine the potential durability, samples are taken from the supplied concrete and set to a laboratory where they are wet cured for up to seven days. These conditions provide the best possible site-simulated curing conditions and the potential durability characteristics will be maximised. Generally, laboratory cured samples will yield better durability indices than site cured concrete. To account for expected differences, limiting values have been placed on the test results as discussed below (Alexander et al, 2008):

As delivered (laboratory-cured)

Oxygen permeability test results from laboratory-cured samples should be at least 0.10 greater than the specified limiting values from the deemed-to-satisfy or rigorous approach.

Chloride conductivity test results from laboratory-cured samples should not be greater than 0.90 of the specified limiting values from the deemed-to-satisfy or rigorous approach.

As built (site-cured)

Site-cured samples from the as built site should be taken between 28 and 35 days after placement.

Oxygen permeability test results from laboratory-cured samples should be at equal to or greater than the specified limiting values from the deemed-to-satisfy or rigorous approach.

Chloride conductivity test results from laboratory-cured samples should be less than or equal to the specified limiting values from the deemed-to-satisfy or rigorous approach.

2.3.8 Use of durability indices by SANRAL

The South African National Roads Agency Limited (SANRAL) has included durability indices in specifications for concrete design. Acceptance criteria have been given for limiting values of water sorptivity, oxygen permeability and chloride conductivity. Similarly, guidelines have been given for the acceptance of concrete cover. Additionally, guidance has been provided for designers and contractors in order to clarify liability.

Table 2.8: SANRAL acceptance criteria for water sorptivity and OPI

Acceptance criteria	Test description	
	Water sorptivity (mm/√hr)	**Oxygen permeability (log scale)**
Concrete made, cured and tested under laboratory conditions	Average of 4 tests	> 9.80
Full acceptance of in-situ concrete	Value above x 1.15 (Max = 12.0)	> 9.70
Conditional acceptance of in-situ concrete (with remedial measures approved by the engineer)	12.0 - 15.0	8.75 - 9.70
Rejection	> 15.0	< 8.75

Chloride conductivity values are provided in Table 3.7. The maximum water:binder ratio is limited to 0.55 for any concrete to be used in the environmental classes outlined in Table 3.7. Chloride conductivity values are used during mix design and material selection. Additionally, limiting values are used during early construction as a means of quality control.

Design engineers will specify durability indices in conjunction with a minimum cover depth to achieve the specified service life. Like durability indices, acceptance criteria have been given for cover depth and are detailed in Table 3.9.

Table 2.9: SANRAL acceptance criteria for cover depth

Specified cover (mm)	Acceptance range			
	Min		Max	
	Overall	Individual bar	Overall	Individual bar
30 to 80	85% of specified cover	75% of specified cover	Specified cover + 15 mm or where member depth is less than 300 mm the limit accepted in writing by design engineer	Specified cover + 25 mm or where member depth is less than 300 mm the limit accepted in writing by design engineer

2.3.9 Solutions for structures failing to meet durability specifications

The South African durability index approach uses carbonation and chloride ingress models to predict the service life of reinforced concrete structures. Already discussed in this chapter are the durability indices of carbonation, chloride ingress and water sorptivity however a graphical representation is required to further illustrate the way in which indices link to carbonation and chloride ingress. Two example scenarios with assumed input parameters are presented for carbonation and chloride ingress.

Carbonation

The South African durability approach carbonation model uses three input parameters to predict the carbonation depth after 50 years. The input parameters used are OPI (laboratory test), binder type and environmental conditions (relative humidity). The binder type used in this work was fly ash and the OPI value obtained from the experimental procedure was 9.00. The environmental condition is assumed to be 60% RH i.e. the most extreme environment for carbonation to occur.

Assumed Input Parameters	Binder type:	30% Fly ash
	Carbonation environment:	60% RH
	OPI value from laboratory investigation:	9.00

Output Parameters	Carbonation coefficient:	11.52 m/s
	Power:	0.4

Based on input parameters 30% fly ash mix, OPI = 9.00 and RH = 60%, the South African durability index approach carbonation model produces a carbonation coefficient = 11.52 m/s and power = 0.4. For the output parameters values calculated from the model, the relationship presented in Figure 2.6 exists. Thus, a graphical means of predicting carbonation depth is obtained. The input parameters of the model are easily changed to suit specific requirements.

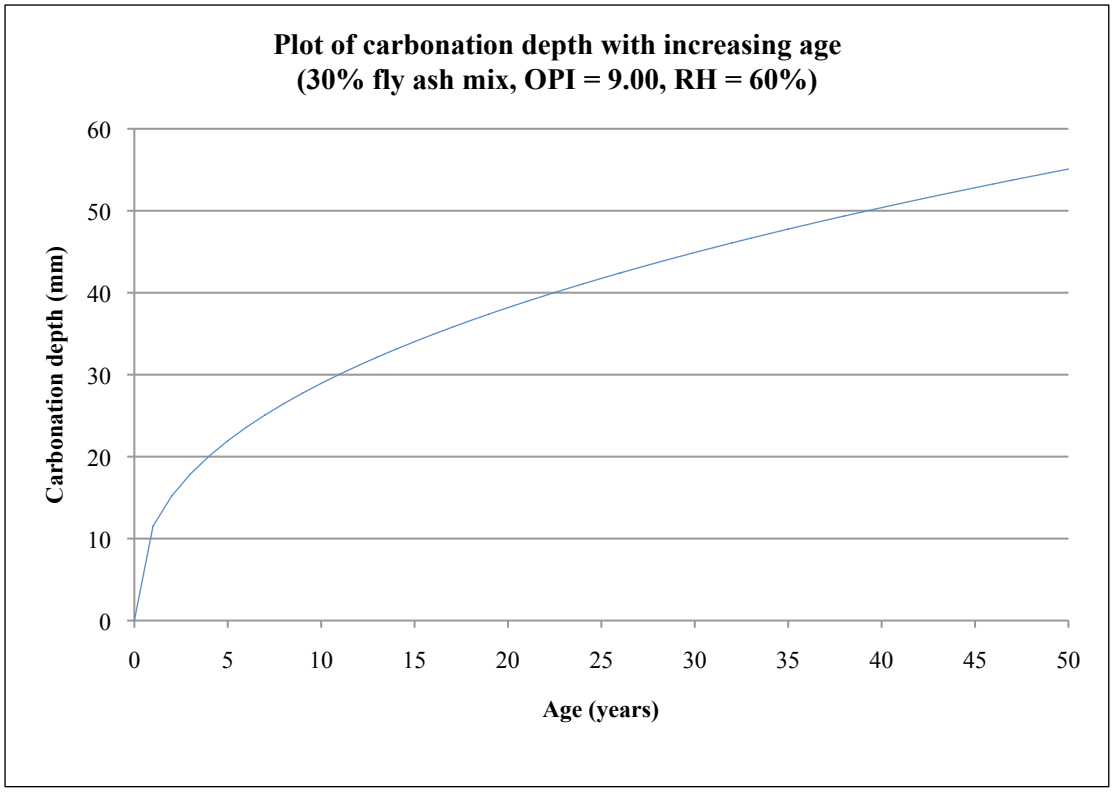

Figure 2.6: South African durability index approach carbonation model

Chloride ingress

The South African durability index approach chloride ingress model assesses the ingress of chloride ions using four input parameters. The input parameters are binder type, exposure conditions, exposure duration and CC value (laboratory test). In this work, 30% fly ash binder was used and the CC value obtained from the laboratory evaluation was 1.00 mS/cm. Extreme exposure conditions were chosen as the worst case for chloride ingress and exposure time was chosen to be 50 years.

Assumed Input Parameters	Binder type:	30% Fly ash
	Chloride exposure:	Extreme
	CC value from laboratory investigation:	1.00 mS/cm
	Exposure time of concrete:	50 years

Output Parameters	Surface chloride concentration:	4.50%
	Diffusion coefficient (2 year):	2.2×10^{-8} cm^2/s
	Diffusion coefficient (50 year):	2.5×10^{-9} cm^2/s

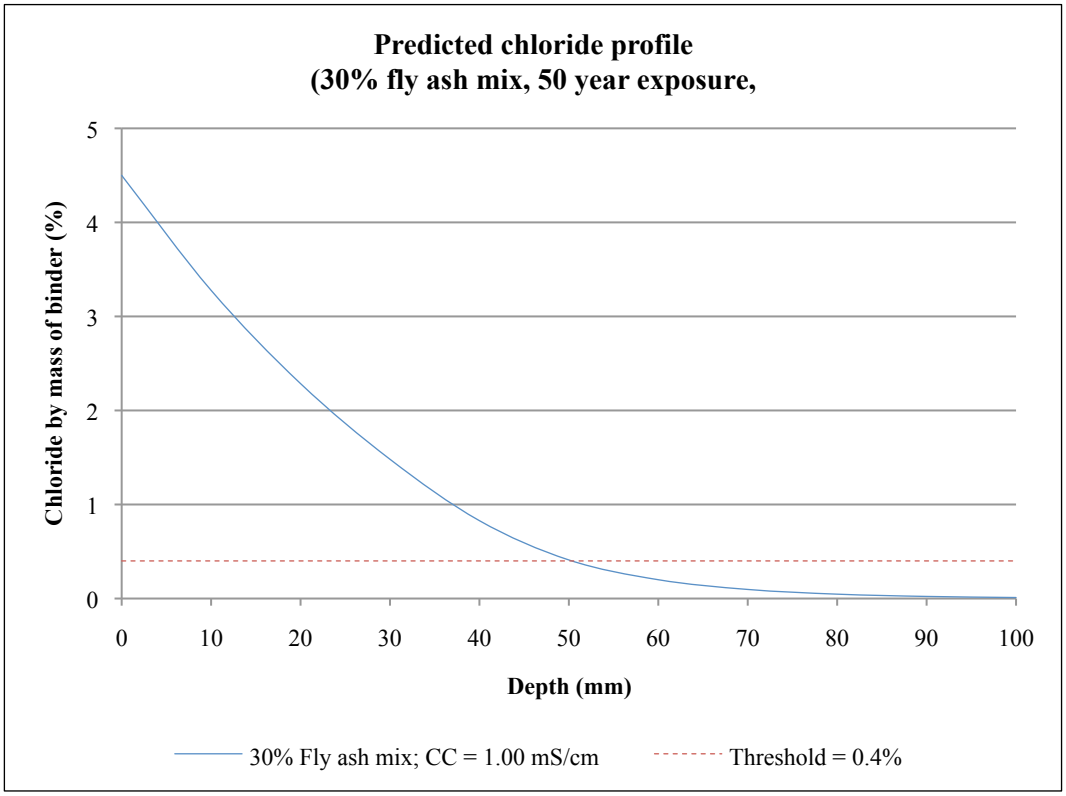

Figure 2.7: South African durability chloride ingress model

Based on input parameters 30% fly ash mix and CC = 1.00 mS/cm, the South African durability index approach chloride ingress model produces a surface concentration = 4.50%, 2 year diffusion coefficient = $2.2 \times 10^{-8} cm^2/s$ and 50 year diffusion coefficient = $2.5 \times 10^{-9} cm^2/s$. For output parameters calculated from the chloride ingress model, the relationship presented in Figure 3.7 exists. Thus, a graphical means of predicting the chloride ingress is obtained. The model can be adjusted such that the depth of chloride ingress is calculated for different ages. In other words, if the depth of chloride ingress is required to be know after 10 years, then the input parameters can easily be changed to accommodate specific requirements.

Making use of the South African durability index approach models for carbonation and chloride ingress, engineers are able to predict the expected service life of reinforced concrete. If concrete is designed, mixed and placed in the correct manner, then it is considered to be inherently durable. However, if concrete fails to meet durability requirements (as predicted by the models) then additional service life must be obtained through other means; such as the use of coatings.

2.4 Protective surface treatments for concrete structures

A multitude of products and systems for the repair and protection of concrete structures is available for use. In general, corrosion can be caused by a loss of concrete cover, an overall reduction of alkalinity (carbonation) and the ingress and attack of corrosion promoting contaminants (chlorides) (Raupach and Röβler, 2005). This work will only discuss the use of surface treatments for concrete structures to improve durability characteristics. Surface treatments have many applications in the protection of concrete structures. They can be used to improve the resistance to carbon dioxide and chloride ingress (responsible for the onset of corrosion in reinforced concrete). Furthermore, surface treatments can reduce the moisture content in carbonated concrete to values that will not permit corrosion to proceed provided there are no chlorides present (Pullar-Strecker, 2002; Boxall, 2002).

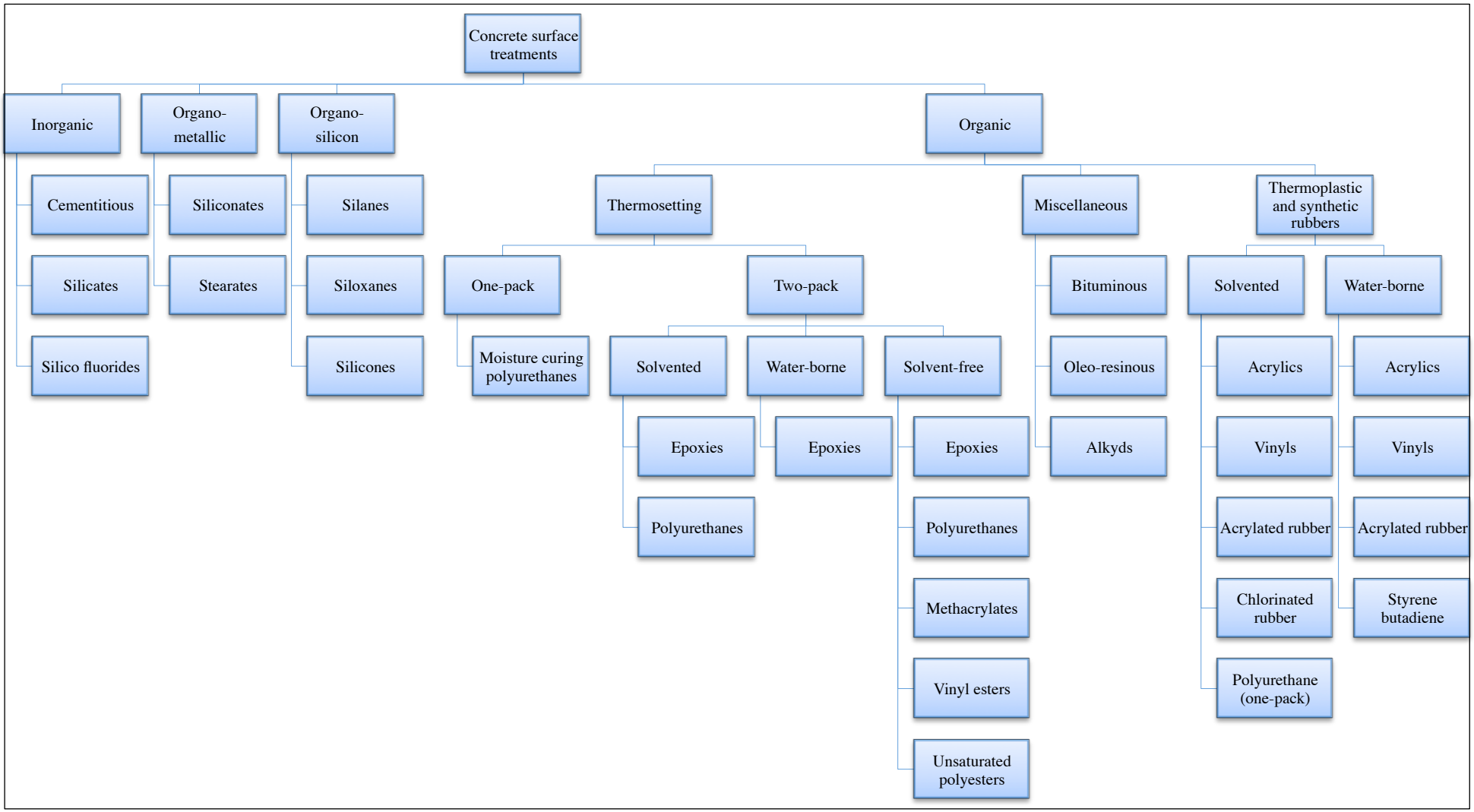

Figure 2.8: Classification of concrete surface treatments by composition (Khan, 2000)

Surface treatments are frequently used in conjunction with repair methods. In such cases, surface treatments are used to ensure that further entry of contaminants does not occur in the repaired area. The benefit of surface treatments is two-fold; they provide protection as well as providing cosmetic improvements to structures by hiding repair work. The use of surface treatments has been limited because engineers do not consider their use to be permanent. Rather, they have in the past been used as a temporary measure to slow down the formation of cracks caused by corrosion whilst other more 'permanent' protection methods are considered. However, for certain projects, surface treatments are able to provide a long-term solution for the protection of concrete structures if the guidelines for application, monitoring and maintenance are rigorously followed. In many cases, the product may have to be re-applied but generally, the cost of such activities is substantially less than other methods of protection (Pullar-Strecker, 2002; Boxall, 2002).

There are a vast number of surface treatments available to prevent the ingress of corrosion causing agents. Depending on the project, the engineer must select an appropriate coating. For instance, if carbonation is to be protected against, then the engineer must select a product that will prevent the ingress of carbon dioxide. Such a surface treatment may not prevent the ingress of moisture and would therefore not be effective in preventing the ingress of chlorides. A discussion of the available surface coatings and the associated protection mechanisms is therefore necessary (Keer, 1992).

A classification system is required to group the vast number of concrete surface treatments available into broad categories. Generic groups are determined by the chemical composition of each product. More specifically, generic groups are usually determined by the resin fraction composition. The system of grouping coatings according to similar chemical attributes is useful as products from the same generic group will tend to possess similar performance characteristics. Classification of concrete surface treatments by chemical composition is presented in Figure 3.8 (Khan, 2000).

2.4.1 Pore liners

Pore liners contain hydrophobic materials that are able to penetrate the concrete surface, line the surface of the capillary pores and resist the ingress of moisture. The use of pore liners may be advantageous over coatings and renderings because they do not form a physical barrier on the concrete surface which may at a later stage be affected by ultraviolet radiation and other forms of weathering. Longevity of the protective properties of the products is therefore increased to a certain extent (Kay, 1992).

Hydrophobic agents are applied to concrete structures to make the surface resistant to water. Hydrophobation of the surface prevents water and other dissolved contaminants from entering the concrete through capillary action by altering the surface tension of the pores. Furthermore, staining by the agglomeration of algae, moss and fungus is reduced. Hydrophobic agents allow for the movement of carbon dioxide, oxygen and other gases (Raupach and Röβler, 2005; Pullar-Strecker, 2002). In some cases, the use of hydrophobic pore liners may encourage the passage of gases because moisture that usually prevented movement no longer exists in the capillary pores. In other words, capillary pores containing water in untreated concrete (after rainfall for instance) will prevent the ingress of gasses. It is intuitive to assume that the risk of carbonation in structures treated with hydrophobic agents may be increased, but the reduced moisture content normally offsets this effect. Due to the reduced moisture content, carbonation will not occur (Hunkeler, 2005). Because the movement of gases is permitted, moisture vapour is allowed to move freely through the capillary pores and concrete is able to breathe. Generally, concrete will dry out over time because there is an overall reduction in

the moisture content. Additionally, the reduced moisture content will hinder corrosion at a later time (Kay, 1992).

Depending on the porosity of the concrete, penetration depths of up to 5 mm can be expected when concrete is treated with hydrophobic agents. The effectiveness of hydrophobation increases with penetration depth. Evidence of the coating (in the form of a film) is not visible on the concrete surface. Rather, depending on the permeability of the concrete, the surface treatment will travel into the concrete and line the pores. It is important to note that pores are not filled with the use of hydrophobic agents. Silicone based compounds (silanes and siloxanes) form methyl siliconate when they react and bond with concrete substrates. Methyl siliconate is water-soluble and over time may be leached out by rainwater rendering the protection mechanism ineffective. This process is dependent on the chemical makeup of specific materials and exposure conditions. Reapplication of hydrophobic agents may be necessary because the effectiveness is limited to certain durations. Manufacturers warrant products based on material composition which is normally a closely guarded trade secret. (Raupach and Röβler, 2005; Thomas, 2002). Moisture under low pressure is not able to penetrate the hydrophobic capillary pores. However, water under pressure may be forced through the capillary pores yielding the material ineffective against moisture ingress. Thus, the application of hydrophobic agents should be avoided in conditions where ponding may be likely (Kay, 1992). Materials based on silicone compounds are the most important hydrophobic treatments. This group of materials is produced from inorganic materials containing oxygen, silicon and hydrocarbons (Keer, 1992).

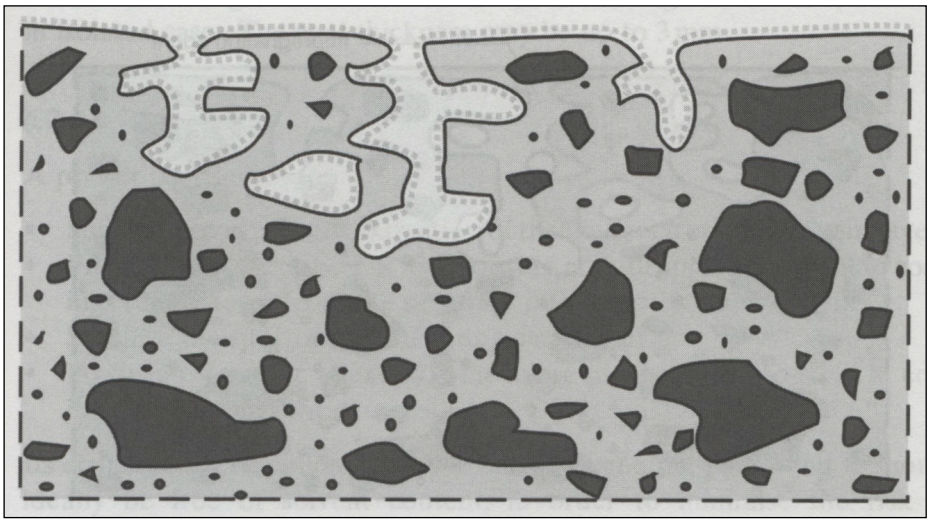

Figure 2.9: Illustration of a pore-lining surface treatment (Raupach and Röβler, 2005)

Silicon-based compounds (siloxanes)

Pore liners produced from silicon-based compounds are given the simple name silicones. A discussion of the silicone group is needed to understand the associated mechanism of protection with regards to water repulsion (Keer, 1992; Thomas, 2002).

Silicon and carbon are similar with respect to the way they are able to form long chain compounds. Long chain silicon compounds consist of oxygen atoms, silicon atoms and alkyl radicals. A long chain is formed from alternating oxygen and silicon atoms. The long chains with the attached alkyl radicals are known as siloxanes (Figure 3.7). Under certain conditions, siloxanes can become cross-linked to form silicone resins known as polysiloxanes (Thomas, 2002). The characteristics of the resulting polysiloxanes will depend on the size of the attached radicals but many of these silicone resins produce waterproofing properties for the surface treatment. Silicone resins are readily dissolvable in organic solvents. Once dissolved, silicone resins can be applied as surface treatments to concrete. The resulting mixture of solvent and silicone resin when applied to concrete will penetrate to shallow depths below the surface and will form a water repellent layer once the solvent evaporates (Kay, 1992; Keer, 1992).

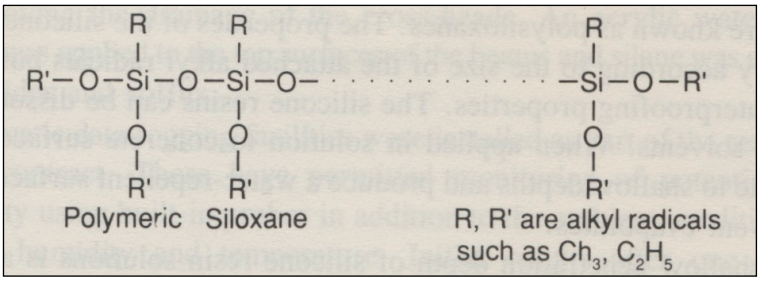

Figure 2.10: Siloxane chain showing the oxygen atoms and the alkyl radicals (Kay, 1992)

Silane-based compounds (silanes)

Silane-based compounds are able to penetrate concrete to depths greater than silicon-based compounds below the surface. Silanes can be used in a diluted or undiluted state. Typically, white spirit or ethanol is used as the diluting agent, which is able to react with moisture to form silicone resin (Keer, 1992). Essentially, silanes and silicones are the same compounds except that silanes have a lower molecular weight. It is due to the lower molecular weight of silanes that they are able to achieve greater depths of penetration. Intermediate products, silanol and alcohol, are produced when silanes are exposed to water. Silanes polymerise and join together (by cross-linking) on the surface of the concrete. Reactions with silicate molecules in the cement paste cause silanes to chemically bond with the concrete surface (Kay, 1992). The reaction of silanes is not spontaneous and occurs over a period of a few days, but catalysts can be added to increase the rate of reaction (Keer, 1992; Thomas, 2002). Additionally, silanes may be added to other coatings to ensure good bonding to the substrate through due to its enhanced cross-linking properties. In such cases, a thin-pigmented film may form on the concrete surface, but permeability will not be affected (Bassi and Boxall, 2002).

The conversion of silane to silanol requires the presence of water. During application, it is possible for moisture to evaporate before the silane has had a chance to react, which would yield the coating ineffective. Thus the use of larger molecules in the form of short chain polysiloxanes is often preferential because they

are able to remain in position for longer until the conditions are right for polymerisation and cross linking to occur. The surface treatment will not achieve the required water repellent characteristics if polymerisation and cross linking does not occur (Kay, 1992; Thomas, 2002).

Silane/siloxanes

Silanes are able to penetrate deeper into concrete substrates due to relatively small molecule sizes. However, small molecules are also responsible for the volatility of silanes. For this reason, silanes and siloxanes are often combined to form materials that are less volatile but are still able to penetrate concrete to depths greater than siloxanes. Silane/siloxane materials harness are able to penetrate deeper into concrete due to the small silane molecules while the larger siloxane molecules ensure that evaporation is reduced so that full polymerisation and cross linking occurs (Thomas, 2002).

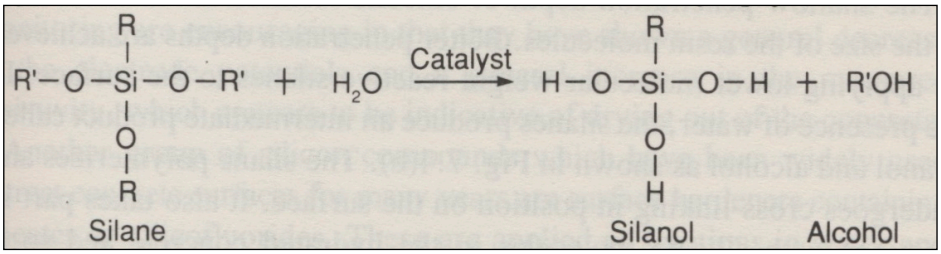

Figure 2.11: Silane chain showing oxygen atoms and alkyl radicals (Kay, 1992)

Hydrophobic agents like silanes have the ability to promote the drying of the concrete surface through the removal of water. It is possible for this dry layer of concrete to reach the surface of the reinforcing steel and even in high concentrations of chlorides, corrosion can be halted because moisture is no longer present (Kay, 1992). Although an important property of hydrophobic agents, the consideration in this work is limited to corrosion prevention of new structures. Thus, testing and analysis is limited to chloride ingress subsequent to the application of protective surface treatments.

2.4.2 Pore blockers

The primary objective of pore blocking agents is to prevent the ingress of liquids into concrete. Pore blocking materials are able to penetrate 1 to 3 mm into the concrete surface and block pores through the formation of crystals by reacting with the substrate or by chemically hardening. Pore blockers are non-film forming, but rather, form a matrix which is physically bonded to the concrete substrate. The matrix formed by pore blockers permits the movement of water vapour because of its porous structure. The passage of water is prevented due to the hydrophobic nature of pore blocking materials. Most commonly, liquid silicates and silicofluorides are applied to concrete surfaces. Silicate and silicofluoride materials react with calcium hydroxide to form more calcium silicate hydrate or insoluble calcium silicofluoride respectively (Keer, 1992). In other words, these materials act by reacting with the cement paste constituents to form a physical plug in the capillary pores (Kay, 1992; CIRIA, 1987).

Certain epoxies and resins may also be classified as pore blockers because they are able to penetrate the concrete surface and harden inside the substrate. Some pore blocking treatments are applied as renderings that contain active ingredients. These active ingredients are able to penetrate the concrete surface and block the pores so that if the rendering is damaged or spalls away, the original substrate remains intact. For many years, pore blockers have to a large extent been used as a method of improving the abrasion resistance of concrete surfaces. Furthermore, they are able to reduce dusting of concrete floors (Keer, 1992).

2.4.3 Renderings, coatings and sealers

Essentially, there is little distinction between coatings and renderings in terms of material characteristics and function; however, renderings are usually bound by hydraulic cement. The definition of renderings can be extended to include polymer-bound coatings that are normally used to protect concrete against aggressive chemicals. Such an application may be in wastewater treatment plants in hot climates where concrete is constantly subject to the exposure of aggressive chemicals. Coatings are usually polymer based; contain pigment for colour and a filler to provide bulk and thickness. Renderings contain additional inert filler materials (quartz, micas and kaolin) which improve the durability and weathering resistance. Cement based rendering contain polymers to increase the bulk, improve the workability and reduce the permeability of the product. Further advances have led to renderings containing fibres that increase cohesion in the wet state and provide a certain degree of crack and impact resistance to the finished surface (Kay, 1992; Keer, 1992).

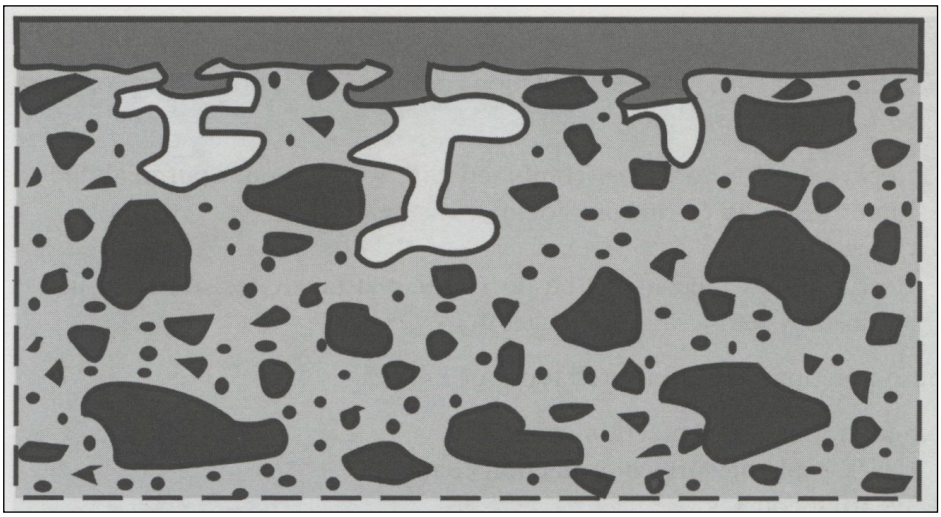

Figure 2.12: Illustration of a coating on a concrete surface (Raupach and Röβler, 2005)

The distinction between coatings and renderings can be further extended to include layer thickness and application technique. Coatings are normally defined as having a thickness of less than 0.5mm and are applied using painting methods (brush, roller or spray). Renderings provide thicker layers than coatings and are in the order of 1mm. Furthermore, renderings are usually applied using plastering techniques (Kay, 1992; Keer, 1992; CIRIA, 1987).

The protection mechanism for coatings and renderings is essentially that same as they provide an external barrier that reduces that rate of liquid and gas ingress. If care is not taken to ensure that the concrete substrate is suitable for the application of coatings, the resulting finish may have little or no effect on reducing the ingress of fluids. Coatings are not designed to fill blowholes occurring on concrete surfaces and pinholes in

the coating may result. Therefore, pore fillers or stoppers are used to fill blowholes with diameters in the range of 1 to 5mm. On rough or uneven concrete surfaces, levelling coats are used to provide a smoother finish onto which the coating may be applied. Failure to level out uneven surfaces results in the coating being very thick in hollows and very thin over bumps. Thus, interruptions in the coating are possible and localised corrosion could result (Kay, 1992).

Coatings and sealers may contain a number of different ingredients. The binding component of coatings and sealers is responsible for the formation of the surface film. Generally, generic type coatings and sealers are named and classified according to the film-forming binder; these include: Epoxies, polyesters, acrylics, polyurethanes, vinyls, butadiene and polyethylene copolymers, alkyds, bitumens and oleo resinous varnishes. The viscosity of coatings and sealers is normally reduced with the use of solvents that act like dilutants. It is important to note that the solvents used for dilution do not dissolve the binder (Keer, 1992).

The composition of coatings and sealers can be adjusted in a number of ways to include plasticizers, catalysts, fungicides, fillers and pigments. Additionally, the solvent content can be adjusted to alter the viscosity. Fillers are used to increase the bulk and abrasion characteristics of the material. Subsequently, the material can be applied in thicker layers and will possess greater resistance against abrasion. Pigments in the form of finely ground powders are added to coatings and sealers for colour. It has also been recognised that pigments will affect the anti-carbonation properties of coatings and sealers (Keer, 1992; CIRIA, 1987).

Sealers have properties that are common to both coatings and pore blockers. They are able to penetrate into the concrete and at the same time form a thin layer on the concrete surface. Very often, sealers are used to improve the characteristics of the concrete substrate. Because of the penetration properties, they adhere well to the concrete and are thus used as primers before the application of coatings (Kay, 1992). Sealers, like coatings are only effective if a continuous surface, free of holes and of uniform thickness is formed to act as a barrier against the ingress of water, oxygen and contaminants. Sealers may commonly be classified as paints and often contain pigments for the provision of colour. Applied in two or more layers, sealers have a dry film thickness in the region of 100 to 300 μm, but, if required, greater thicknesses can be achieved (Keer, 1992).

It is important to bear in mind that concrete is a highly alkaline environment and the chosen coating or sealer must be non-saponifiable (resistant against alkaline attack). Thus, certain oil-based formulations must be avoided or used in conjunction with an alkali-resistant primer. The film-formation process of coatings and sealers may be attributed to a number of different mechanisms including evaporation (solvent or dispersion agent like water), chemical reaction (stimulated by a catalyst), reaction with moisture (from the substrate or the atmosphere) or reaction with oxygen (oxidation) (Keer, 1992; CIRIA, 1987).

2.5 Protective surface treatments to prevent corrosion in reinforced concrete structures

2.5.1 Surface treatments to control carbonation

Coatings and sealers are primarily used to control the ingress of carbon dioxide. The surface film produced by coatings and sealers is able to limit the movement of carbon dioxide into concrete. Anti-carbonation coatings have in the past been assessed in a number of different ways including (Keer, 1992):

- Carbonation measurement of treated concrete samples exposed to natural conditions
- Carbonation measurement of treated mortar samples exposed to carbon dioxide under controlled conditions (laboratory based)
- Transmissibility of carbon dioxide through a film of the coating applied to a paper or card board substrate (laboratory based)

Samples exposed to natural conditions will provide the most realistic results while laboratory tests are accelerated and will provide results that may be useful on a comparative level. It is useful to test the amount of carbon dioxide passing through the coating film so that one may obtain the diffusion resistance coefficient for carbon dioxide (μ_{CO2}). This dimensionless value of the diffusion resistance coefficient is used in conjunction with the coating thickness to obtain a diffusion equivalent air thickness layer (Keer, 1992).

$R = \mu S$

Where: R = diffusion equivalent air layer thickness (m)
μ = diffusion resistance coefficient
S = coating thickness (m)

Thus, one can see that an increase in either the coating thickness or the diffusion resistance coefficient will increase the diffusion equivalent air thickness layer. On this basis, the relative effectiveness of anti-carbonation coatings can be assessed both before and after accelerated cyclic weathering (Keer, 1992).

In Europe, it has been widely accepted that a coating for anti-carbonation requires an R-value of 50 m. The R-value for 25 mm concrete cover, made from ordinary Portland cement, is in the region of 5 m. While limiting the flow of carbon dioxide, the film of anti-carbonation coatings needs to allow the passage of water vapour. This movement is easily allowed because the molecules of carbon dioxide are larger than those of water vapour. Failure to permit the movement of water vapour will cause pressure to build up behind the coating. A further criterion for anti-carbonation coatings is the value of $\mu_{H2O}S$ must be less than 4 m (where, μ_{H2O} is the diffusion resistance coefficient for water). The equivalent air layer thickness values of water and carbon dioxide are not an absolute measure of coating quality and deviations in quality have been observed in the past. In other words, good resistance to carbonation has been observed with so-called poor quality coatings and vice versa (Keer, 1992; Davies et al, 2002).

2.5.2 Surface treatments to control moisture and chloride ingress

The prevention of water (as a liquid) movement is an important characteristic of surface coatings to possess if they are to successfully prevent the ingress of chlorides. Chloride ions enter concrete due to capillary action and diffuse through saturated pores. Thus, if a surface coating can prevent water ingress then chloride ion ingress will also be prevented (Keer, 1992).

Coatings, sealers, renderings, pore liners and pore blockers can be used to prevent the ingress of water and chlorides. A variety of tests have been performed on such surface treatments to assess their ability to prevent water and chloride ingress. Such tests include (Keer, 1992):

- Permeability under high pressure
- Immersion and the associated weight gain due to absorption
- Initial surface absorption tests
- Moisture penetration under shallow ponding
- Chloride diffusion through thin sections of mortar coated samples
- The onset and measurement of corrosion in treated samples

The results of generic-type treatments have been varied and inconsistent highlighting the need for standardised tests that will provide a common basis for all surface treatments to be compared against. Furthermore, engineers have been left to ponder over the data provided by manufacturers because of the inconsistency of the testing procedures. Thus, for this reason, it has been difficult for engineers to make informed decisions for the prevention of water and chloride ingress (Keer, 1992).

In an American experimental program, it was found that silane-based surface treatments are highly effective in reducing the ingress of moisture and chlorides. This evidence was further supported by a survey in which previously silane-treated structures were assessed because it was clear that moisture and chloride ingress was to a large extent prevented (Keer, 1992).

Renderings applied to structures that to some extent possess pore-blocking capabilities have in the past been highly successful in the prevention of moisture and chloride ingress. However, renderings that have flaked off (for whatever reason) but still act as pore blockers have reduced capabilities in the prevention of water and chloride movement. Similar results have been observed in pore blocking surface treatments (Keer, 1992).

2.6 Evaluating the protective properties and durability of protective coatings

Much research has been carried in the field of concrete repair methods and materials. Of particular interest to this project is the durability of concrete surface coatings. Concrete surface coatings can provide a relatively inexpensive method of protection to a structure and effectively increase the service life of concrete that has failed to meet limiting durability requirements. One must use these coatings with caution however as they may deteriorate after only a few years in service yielding them ineffective as a protective system for the reinforcing steel. From literature, a number of laboratory projects have been conducted to investigate the durability and performance of protective surface treatments.

2.6.1 Adhesion of coatings

Liu and Vipulanandan, 2005 investigated the bond strength of four coatings on a dry and wet substrate with and without a 105 kPa backwater pressure over a period of two years. Five failure types were observed for the four coatings under the conditions described. Although the coatings were all epoxy based, a range of adhesion results was observed. It was found that the adhesion to dry concrete was better than the adhesion to wet concrete. It was also found that the bond strength for two coatings reduced over time on both wet and dry substrates.

Raupach and Wolff, 2008 investigated the effect of internal capillary pore pressure on the blistering and delamination of coatings. Frequently, epoxy based coatings will begin to blister and delaminate due to the humidity and alkaline environment of the concrete substrate. The project discovered that blistering and delamination of epoxy coatings was due to the internal pore pressure of the concrete exceeding the pull-off strength (adhesion) of the coating. Furthermore, internal pressures of only 10% of the adhesion strength may be high enough to cause localised blistering of the coating.

The adhesion of three elastomeric coatings applied to carbonated concrete was investigated by Seneviratne, 2000. Coatings were applied to a carbonated concrete structure suffering from reinforcement corrosion. The intention was to halt further corrosion from occurring by applying coatings to prevent moisture ingress. It was found that two of the coatings effectively reduced moisture ingress for two years; the bond strength of these coatings was found to be highly variable. The third coating was able to reduce moisture ingress for five years; the corresponding bond strength of the third coating was found to be relatively low but consistent over the test period.

2.6.2 Previous research on the use of concrete coatings used to improve durability

Batis et al, 2003 investigated the effect of an aqueous acrylic dispersion, silicate based inorganic coating and the combined use of a corrosion inhibitor and inorganic coating at providing protection to reinforced concrete in an aggressive chloride environment. Reinforced concrete samples were coated using an aqueous acrylic dispersion and a silicate based inorganic coating. Some samples were cast using a corrosion inhibitor. The samples were then placed in a sodium chloride solution to simulate aggressive corrosion conditions. It was found that the uncoated control samples experienced the most corrosion. The acrylic dispersion coating provided effective protection in the aggressive environment. The samples cast using an inhibitor and coated with the inorganic coating provided protection almost equal to the acrylic dispersion. The inorganic coating alone was ineffective at providing protection. Protection provided by inhibitors is linked to the ratio between inhibitor and chlorides (inhibitor:chlorides). Likewise, the corrosion inhibitor was found to be ineffective as the dosage was found to be insufficient for the aggressive environment used in the study.

Al-Zahrani et al, 2002 investigated the effectiveness of various coating types at preventing corrosion from occurring under accelerated corrosion conditions. Additionally, water absorption, water permeability, chloride permeability and pull-off strength were evaluated under accelerated weathering conditions. Three generic type coatings (2 polymer-based, 1 cement based polymer-modified and 1 cement based) were applied to reinforced concrete samples. The samples were then subjected to accelerated corrosion conditions so that the corrosion initiation time could be determined. The physical properties were investigated after an accelerated weathering regime of wetting/drying and heating/cooling for five months. After weathering, the

water absorption, water permeability, chloride permeability and adhesion were evaluated. The polymer-based coatings showed the best results in the accelerated corrosion and physical tests. The cement based polymer-modified and cement based coatings did not perform as well as the polymer-modified coatings. More importantly however, the study showed that water absorption, water permeability and chloride permeability correlate well with accelerated corrosion performance. Water absorption was found to be the simplest property which can be used to predict the potential corrosion protection of coatings.

In a study by Almusallam et al, 2003, the durability of concrete was evaluated after it had been coated with five generic type coatings – acrylic, polymer emulsion, epoxy resin, polyurethane and chlorinated rubber. Two coatings obtained from different manufacturers represented each of the generic groups. Samples of coated and uncoated concrete were assessed for chloride permeability, chloride diffusion and water absorption. It was found that the polyurethane, chlorinated rubber and epoxy coatings were effective in reducing the electrical resistivity of concrete according to the chloride permeability and water permeability values. Coated mortar specimens were submerged in a 2.5% sulphuric acid solution for a period of 60 days to reproduce chemical attack conditions. It was found that the epoxy and polyurethane coatings were still intact after exposure to the sulphuric acid solution whereas the other coatings had completely disintegrated. The epoxy and polyurethane coatings performed the best in the water absorption test. Results from the chloride diffusion test, showed that polyurethane, epoxy and acrylic coatings performed the best. Using the data from the chloride diffusion tests, it was estimated that corrosion could take up to 30 years to occur with the use of polyurethane coatings while in uncoated samples, corrosion was estimated to start occurring within 1 year. While performance of polyurethane and epoxy coatings was found to be superior than the acrylic, chlorinated rubber and polymer emulsion coatings, variations in the performance between generic types from different manufacturers was found to be significant. Thus, highlighting the need for performance trials to be conducted prior to the selection and use of coatings. Additionally, coating specification should not be based generic groups.

Wei et al, 1989, carried out an investigation into the carbonation resistance of 15 coatings and coating combinations. Mortar samples were prepared and coated with 15 different systems. The samples were then exposed to artificial weathering which consisted of 2 hours UV radiation exposure followed by 20 minutes water spray for periods of 500, 1000, 1500 and 2000 hours. On removal from the weathering chamber, samples were placed in a carbonation chamber (15% carbon dioxide and 78 ± 2% relative humidity) for a period of 14 days. The depth of carbonation was found to increase with increased periods of weathering. Emulsion type coatings proved to provide the least protection from carbonating environments due to the formation of pinholes and cracking caused by artificial ageing. Film formation and thickness were found to be essential parameters for carbonation resistance. Polyurethanes and acrylic polymers were found to possess the highest carbonation resistance. Furthermore, a coating thickness of at least 200 microns in 2 to 3 coats was recommended to provide good protection against carbonating environments. Although artificial weathering and carbonation conditions in this study were severe, protective properties (and potential durability) of coatings could be assessed in a relatively short period of time.

Maslehuddin et al, 2005, carried out a test programme to evaluate the performance of 10 repair systems exposed to 7 environments - marine (UV radiation and salt spray), below ground (chloride-sulphate solution), acid (2% hydrochloric acid), sulphur fumes, potable water, saline water, and fire damage. Repair systems consisted of combinations of repair mortars, bond coats, steel primers and surface coatings. Large reinforced concrete beams and slabs were prepared. Parts of the large specimens were then broken out

(exposing reinforcing steel) and repaired using different repair systems for each of the exposure conditions. The repaired beams were then exposed to differing exposure conditions - exposure continued for a period of 8 months during which time, performance of the repair systems was monitored using corrosion potentials. Damage to the applied coatings was visually monitored throughout exposure. Control samples were used as a basis for comparison throughout the investigation. After exposure, the pull of strength (adhesion) of coatings was evaluated. Finally, the rebar was broken out and the extent of corrosion was visually inspected. There was no clear distinction between the results obtained for repair systems exposed to different environments. Based on this study, the authors have recommended a number of different repair systems each of the exposure conditions. Varied results from differing systems have stressed the importance of performance-based trials prior to the application and specification of repair systems.

2.6.3 Non-destructive evaluation of surface treatments

Previously, non-destructive methods for evaluating coating properties have not been available. Potentially, the NMR-Mouse (Nuclear Magnetic Radiation Mobile Universal Surface Explorer) can be used to evaluate the thickness of coatings (as well as individual layers of multi layer systems), water ingress through surface treatments, drying process of concrete after surface treatment application, changes due to weathering (degradation) and quality control of applied materials. The NMR-Mouse works (in a non-destructive) manner by exciting atomic nuclei with magnetic fields and radio frequencies. Two outputs can be produced to determine specific properties - proton density and transverse relaxation times (echo decay curve). Coating thickness is determined using the proton density output at various depth increments (usually 50 μm, but higher resolutions can also be obtained). The echo decay curve produced by the NMR-Mouse is used to determine the water ingress of coatings. Additionally, the effect of weathering on coatings can be assessed using the same echo decay curves as the water absorption of properties coatings are altered after weathering. Although this technology has only recently been adopted for use with concrete coatings, preliminary results look promising for future testing. Further research and calibration will be required before the technology can be used for full scale testing on site (Orlowsky et al, 2008).

The durability of hydrophobic surface treatments is to a large extend unknown. A research project by Raupach and Büttner, 2008, investigated the durability (and possible deterioration mechanisms) of six commercially available hydrophobic surface treatments. Two concrete mixes (differing porosities) were used in the study to evaluate the effect of porosity on the effectiveness of hydrophobic surface treatments. Large concrete slabs were produced from which smaller samples taken, treated with the surface treatments and exposed to artificial ageing by carbonation (2% carbon dioxide for 28 and 35 days), UV exposure (28 days), and a high alkaline environment (pH = 13.3 for 28 and 35 days). The contact angle of distilled water, absorption of water and impregnation depth were measured (both before and after weathering) using traditional laboratory methods. Furthermore, the NMR-Mouse® was used to evaluate some of the samples.

Test results for different concrete grades were similar and no significant relationship between porosity and hydrophobic performance could be established. The hydrophobic surfaces of samples exposed to the alkaline environment were not in direct contact with the solution. Rather, samples were placed into a bath of solution and movement of the solution to the treated surface was via capillary action. Greater impregnation depths after alkaline solution exposure were accredited to the increased cross-linking reactions occurring as a result of the alkalinity. Long-term studies are currently underway to verify this observation. Measurement of the contact angle revealed that surface repellency of the immediate surface had decreased after UV exposure.

Further investigation into the effect of surface repellency on overall performance is required to fully understand the effect of UV radiation on hydrophobic surface treatments. Changes in the pore structure associated with carbonation were observed to have little effect on the surface contact angle of water. Performance in terms of overall water absorption are however dependent on product composition and should be evaluated prior to use.

The NMR-Mouse was able to verify the impregnation depth of the coatings non-destructively. Furthermore, the NMR-Mouse was able to identify changes in the surface of the concrete exposed to UV radiation, thus verifying the results obtained from traditional test methods.

2.6.4 Overview of testing carried out on surface treatments

An overview of testing carried out on various concrete surface treatments is presented in Table 3.10. The coating types under evaluation, associated protective properties and summary of outcomes is given for each of the studies discussed in Sections 3.6.1 to 3.6.3.

Table 2.10: Summary of testing carried out on concrete surface treatments

Protection system(s)	Parameter(s) tested	Performance assessment	Reference
Four epoxy based coatings	Adhesion of coatings exposed to backwater pressure	• A range of failure modes was observed • Adhesion of coatings on dry concrete greater than wet concrete • Bond strength affected by time	Liu and Vipulanandan, 2005
Epoxy based coatings	Adhesion of coatings	• Blistering and delamination of coatings is caused by internal pore pressure	Raupach and Wolff, 2008
• Aqueous acrylic dispersion • Silicate based inorganic coating • Combined use of corrosion inhibitor and inorganic coating	Use of coatings to control moisture ingress in an aggressive chloride environment	• Uncoated control samples experienced the most corrosion • The acrylic dispersion coating provided effective protection in the aggressive environment • The samples cast using an inhibitor and coated with the inorganic coating provided protection almost equal to the acrylic dispersion • The inorganic coating alone was ineffective at providing protection • The corrosion inhibitor alone was ineffective at controlling corrosion	Batis et al, 2003

Table 3.10: Summary of testing carried out on concrete surface treatments (continued)

Protection system(s)	Parameter(s) tested	Performance assessment	Reference
Three elastomeric coatings	Moisture ingress control in carbonated concrete	• Corrosion in carbonated concrete was halted by controlling moisture ingress • Adhesion of coatings to carbonated concrete was found to be variable	Seneviratne, 2000
• Two polymer-based coatings • Cement based polymer-modified coating • Cement based coating	• Prevention of corrosion under accelerated conditions • Water absorption • Water permeability • Chloride permeability • Adhesion	• The polymer-based coatings showed the best results in the accelerated corrosion and physical tests • The cement based polymer-modified and cement based coatings did not perform as well as the polymer-modified coatings in any of the assessed areas • Water absorption, water permeability and chloride permeability correlated well with accelerated corrosion performance • Water absorption was found to be a good indicator of corrosion protection potential	Al-Zahrani et al, 2002

Table 3.10: Summary of testing carried out on concrete surface treatments (continued)

Protection system(s)	Parameter(s) tested	Performance assessment	Reference
Six commercially available hydrophobic surface treatments	• Two concrete mixes with different porosities • Accelerated carbonation • UV exposure • Exposure to high alkaline environment	• Surface repellency of the immediate surface had decreased after UV exposure • No significant relationship between porosity and hydrophobic performance was observed • Carbonation had little effect on the surface repellency • Performance in terms of overall water absorption was dependent on product composition and should be evaluated prior to use	Raupach and Büttner, 2008

Table 3.10: Summary of testing carried out on concrete surface treatments (continued)

Protection system(s)	Parameter(s) tested	Performance assessment	Reference
Two of each of the following coatings from different manufacturers were investigated: • Acrylic • Polymer emulsion • Epoxy resin • Polyurethane • Chlorinated rubber	• Chloride permeability • Chloride diffusion • Water absorption • Acid attack	• Polyurethane, chlorinated rubber and epoxy coatings were effective in reducing the electrical resistivity of concrete according to the chloride permeability and water permeability values • Epoxy and polyurethane coatings were still intact after exposure to the sulphuric acid solution whereas the other coatings had completely disintegrated • Epoxy and polyurethane coatings performed the best in the water absorption test • Polyurethane, epoxy and acrylic coatings had the lowest chloride diffusion values • It was estimated that corrosion in samples treated with the polyurethane coating would occur after approximately 30 years, whilst corrosion of uncoated samples was estimated to start within 1 year • Performance between generic types from different manufacturers was found to be significant - coating specification should not be based on generic groups	Almusallam et al, 2003

Table 3.10: Summary of testing carried out on concrete surface treatments (continued)

Protection system(s)	Parameter(s) tested	Performance assessment	Reference
Fifteen coatings and coating combinations	• Accelerated weathering • Accelerated carbonation • Carbonation resistance	• The depth of carbonation was found to increase with increased periods of weathering • Emulsion type coatings provide the least protection from carbonating environments due to the formation of pin holes and cracking caused by artificial ageing • Film formation and thickness were found to be essential parameters for carbonation resistance • Coating thickness of at least 200 microns in 2 - 3 coats was recommended to provide good protection against carbonating environments • Protective properties of coatings could be assessed in a short period under accelerated weathering conditions	Wei et al, 1989
Ten repair systems consisting of: • Repair mortars • Bond coats • Steel primers • Surface coatings	Exposure to seven environments: • Marine (UV radiation and salt spray) • Below ground (chloride-sulphate solution) • Acid attack (2% hydrochloric acid) • Sulphur fumes • Potable water • Saline water • Fire damage	• There was no clear distinction between the results obtained for repair systems exposed to different environments • A number of different repair systems has been recommended each of the exposure conditions • Varied results from differing systems has stressed the importance of performance based trials prior to the specification and application of repair systems	Maslehuddin et al, 2005

2.7 Case studies - Protective surface treatments to prevent corrosion (Bassi and Boxall, 2002)

2.7.1 Protection of concrete bridges, Ireland

A four part coating system was used in Ireland to prevent carbonation and chloride inducted corrosion on 10 newly constructed highway bridges, two culverts and a number of retaining walls. The structures form part of the M50 Northern Cross Motorway in Dublin. Over 15 000 m^2 of concrete was coated with the four-part system to improve the long-term protection of the concrete and reinforcing steel. The project contract specified that a coating system was applied to ensure the specified service life could achieved. It is not certain weather poor quality concrete or design specifications were responsible for the inclusion of coatings into the contract documents.

The surface of the concrete was prepared by high pressure water jetting. A fairing coat was then applied to the surface of the concrete to fill in blowholes and surface defects. The fairing coat provides a smooth, uniform finish for application of subsequent protection layers. A siloxane based impregnation material was used to form a hydrophobic barrier to prevent the ingress of moisture. An acrylate-based primer was then used in the fist stage of the finished surface. Finally, two coats of an acrylate-based surface sealer (with colouring) were sprayed onto the primed surface to form a dry film thickness of 160 µm.

The complete system enables moisture within the concrete to escape while still preventing the ingress of carbon dioxide and chlorides. The system was chosen because of its conformity to the Irish National Roads Authority specifications as well as other contract specific requirements. Minimum active ingredient absorption quantities of siloxane-based sealers were specified by the German Department of Transport Technical Test Standards for Surface Protection System (TP OS, 1990). The materials used in the protection system had to meet certain specifications regarding water absorption, carbon dioxide diffusion, water diffusion and bond strength.

2.7.2 Bridges spanning the Skeidara River, Iceland

In 1974, a network of roads was built to traverse an area of land in extremely harsh exposure conditions. Three road bridges were required to make the project possible. Constructed to steel and concrete, the bridges were exposed to constant moisture spray from the Skeidara River as well as abrasive sand blasting from sand storms in which winds reached speeds of over 100 km/h.

A water based copolymer coating was selected to prevent the ingress of chlorides from the marine environment. The specified product was selected out of a series of products tested to withstand the harsh exposure conditions. In 1996, the bridges had been successfully protected for twenty years and the same product was specified for reapplication on all three bridges.

2.7.3 Bridge protection, Belgium

Bridges in Belgium have been suffering from deterioration caused by the effects of carbonation and chloride induced corrosion. After a 2 year research project as well as substantial testing at the University of Ghent, the Flemish Ministry of Infrastructure and Environment set out requirements for a coating system that could effectively prolong the service life of structures through the provision of additional protection against aggressive environments.

Eleven bridges received treatment based on the outcomes of the research project using a water based acrylic copolymer, anti carbonation coating offering protection against the ingress of moisture and air borne agents. Applied in two coats, the applied system has been seen to provide at least fifteen years of protection.

2.7.4 Protection of Tahtiniemi Bridge, Finland

The Tahtiniemi Bridge spans a length of almost one kilometre and forms part of the Henola Bypass of the Helsinki-Lahti-Lusi motorway. The bridge consists of a cable stayed section as well as twenty columns. Protection against carbonation, chloride attack, moisture ingress and associated frost attack was required to ensure the service life of the structure. The Finnish Road Know-how Group was tasked with finding an appropriate coating that could protect the structure. It was decided to use a water-based material capable of curing in temperatures as low as 3°C. The material chosen forms a completely elastomeric waterproof membrane that effectively resists the ingress of carbon dioxide and chlorides. The product used in the project has been used in practice for over thirty years. It is claimed that the elastomeric properties of the coating are unaffected by age and exposure to UV radiation.

2.7.5 Maintenance of concrete structures: UMIST, United Kingdom

Many of the building at UMIST (University of Manchester Institute of Science and Technology) were constructed in the 1960's and 1970's. The buildings comprised precast and in situ concrete with an exposed white finish. By the mid 1980's, extensive reinforcement corrosion and biological growth caused by sulphur dioxide acid was observed on the campus. Protection from spalling concrete had to be provided around many buildings affected by reinforcement corrosion.

In 1970, one of the structures was repaired with an epoxy mortar and polyurethane coating. The protection system behaved as expected but by the 1980's, weathering had caused the coating to become powdery and ineffective against the ingress of aggressive agents. Corrosion around the edges of the epoxy mortar caused debonding of the repair. Similar materials were then used to recoat the structure however, this was unsuccessful as damage was extensive and large-scale repairs were necessary.

In the 1980's, the protection of concrete structures was investigated at UMIST with special focus on newer materials like polymer-modified mortars and silane based impregnations. In order to develop a strategy to treat damaged concrete structures, an extensive investigation of the structures was required. The cover depth, carbonation depth, chloride ion content, sulphate penetration and cement content were determined. No evidence of alkali silica reaction could be found in the structures. Test results confirmed that cover depth was the most substantial factor leading to corrosion. Interestingly, 84% of samples taken had cover depths less

that the specified 50 mm. Chloride ion content was considered to be the second most important factor. Carbonation and sulphate penetration were insignificant considerations.

Demolition, cladding and coating of the structures were considered as possible solutions to the widespread deterioration. Due to the temporary loss of facilities, a complete rebuild of the structures was not considered a feasible solution and the cost of cladding the structures was considered excessive as a repair solution. Thus, it was decided that concrete coatings could be used to extend the useful service life of the deteriorating structures.

Polyurethanes and acrylic emulsions were considered as possible coating solutions however a pigmented silane based coating system was chosen as the repair material for the project on the basis that it was expected to provide protection for twenty years before recoating was required, it was easy to apply and it was available in different colour shades to restore the appearance of the structures. Pigmented silane systems are relatively thin film forming materials that provide good protection against moisture ingress. The material provides little protection against carbonation which for the purpose of this project was of little importance. Prior to application, corroded areas of concrete were broken out, water-jet cleaned and repaired using a polymer-modified mortar. The coating system was applied in three stages; silane primer, diluted silane colour coat applied to wet primer coat and second silane colour coat applied to dried diluted colour coat.

Later studies proved that the coatings had performed as intended - moisture intake of the concrete was effectively reduced. However, localised chalking of the pigment resulting from poor surface preparation during application was observed in certain areas. Biological growth in certain areas has not been prevented by the coating systems and staining on the concrete continues to be an unresolved problem. The areas did not receive specialist pre-treatment prior to the application of the pigmented silane based coating. In other areas, aesthetic enhancements have been successful and finally. An established maintenance schedule will ensure that the coatings are reapplied at specified intervals (±20 years) to ensure continued protection of the concrete structures.

2.8 Conclusion

Concrete is a porous and permeable material. Therefore, aggressive agents such as carbon dioxide and chloride ions in the form of gases and liquids may enter and migrate through concrete where depassivation of the reinforcing steel may occur. Corrosion can then begin if sufficient moisture is present in the concrete. The South African durability index approach defines the service life of reinforced concrete structures as the time taken for corrosion to initiate. In other words, the service life is the defined as the time taken for deleterious agents to migrate through the concrete cover to the depth of the reinforcing steel (Richardson, 2002; Alexander et al 2008).

Durability is widely affected by different mix designs, proportioning, placing and curing conditions. Therefore, it is recognised that like strength, durability is an important design consideration of reinforced concrete. Furthermore, long-term maintenance costs are greatly reduced through use of good quality concrete (Alexander and du Preez, 2004; Alexander et al, 2008). Steps have been taken to incorporate the South African durability approach into design standards. In particular, SANRAL has adopted durability indices and acceptance criteria into design specifications.

If durability indices are achieved in practice, concrete is considered inherently durable and the specified service life will be expected. However, structures failing to meet durability indices require additional protection to achieve specified service life. Concrete surface treatments provide economical protection from deleterious agents like carbon dioxide and chlorides. A vast number of products are available for the protection of concrete structures and prudent selection must be made in order to ensure continued protection.

The performance and durability of concrete coatings has been assessed in a number of investigations. Analysis under a range of conditions has been carried out on various generic-coating types. Assessment methods and exposure conditions have been inconsistent over a range of studies. Currently, standard performance indicators of performance and durability of coatings and coating systems are lacking. Furthermore, product properties from different manufacturers vary across the generic groups to which they belong. Thus, generalised performance specifications of generic coatings groups should be followed prudently by engineers.

With careful planning and selection, the long-term performance of reinforced concrete structures can be ensured with concrete surface treatments. However, a maintenance schedule should be implemented and followed to guarantee continued protection.

3 Experimental work

3.1 Aims

Concrete produced for construction needs to meet certain criteria in order to meet service life requirements. In the past, strength has been used as indicator of concrete quality and hence durability. Under the South African durability index approach, concrete is required to meet certain minimum requirements in order for it to be considered inherently durable under prescribed exposure conditions. However, when concrete fails to meet certain limiting values, concrete will not meet service life requirements unless mitigating steps are taken to prevent the ingress of deleterious agents.

Surface treatments can be applied to concrete to prevent the ingress of carbon dioxide and (or) chloride ions however, the effectiveness and longevity of commercially available products is largely unknown. In general terms, it was the aim of this work to assess the performance and durability of a number of different surface treatments in a battery of tests under various conditions. More specifically, the aims of the experimental project were to:

- Produce poor quality concrete which would fail under the South African durability approach and require remedial action to fulfil service life requirements

- Apply surface treatments to concrete specimens and assess the performance of each product to prevent the ingress of carbon dioxide and (or) chloride ions after different periods of artificial weathering (0, 3, 6 and 9 years equivalent weathering)

- Assess physical characteristics of the surface treatments such as bond strength, layer thickness and penetration depth

- Use test data in conjunction with the South African durability approach to determine the effectiveness of surface treatments to extend the service life of concrete structures

3.2 Selection of concrete surface treatments

In this work, six different concrete surface treatments were evaluated. Advise from an expert in the industry was sought to provide guidance about the use surface treatments to control the ingress of carbon dioxide and chloride ions in South Africa. The products were chosen as they are widely used in industry to prevent corrosion occurring in reinforced concrete structures. The coatings chosen are based on three broad generic groups; acrylic dispersions (coatings), cement reinforced (renderings) and silanes (pore liners). Full product details can be found in Appendix A. Descriptions taken from the product catalogue has been given as an introduction to the surface treatments evaluated in this work.

Acrylic dispersion

- Composition: One part coating based on UV curing acrylic dispersion with crack bridging properties
- Protection against: Carbon dioxide
- Uses: Protection of concrete structures against carbonation especially in areas where cracking may be expected
- Protection mechanism: Barrier coating

Acrylic resin

- Composition: One part water dispersed acrylic resin
- Protection against: Carbon dioxide
- Uses: Protection of structures where carbonation may be expected. Can also be used to waterproof structures or as a decorative overcoat
- Protection mechanism: Barrier coating

Cement based

- Composition: Two part polymer modified cementitious mortar slurry
- Protection against: Carbon dioxide and chloride ions
- Uses: Protection of structures against the ingress of chloride ions and carbon dioxide
- Protection mechanism: Barrier coating (rendering)
-

Cement based fibre reinforced (FR)

- Composition: Two part elastic fibre-reinforced, cement based flexible coating
- Protection against: Carbon dioxide and chloride ions
- Uses: Waterproofing structures under hydrostatic pressure. Used to protect concrete from the ingress of carbon dioxide and chloride ions. Can be used in concrete where cracking is expected
- Protection mechanism: Barrier coating (rendering)

Silane/siloxane

- Composition: Silane/siloxane combination based, water repellent impregnation
- Protection against: Chloride ions
- Uses: Used in areas where the ingress of chloride ions can be expected. Strong water repellency properties prevent water from entering concrete. Not to be used in areas subject to hydrostatic pressure
- Protection mechanism: Hydrophobic pore liner

Pure silane

- Composition: Pure silane based, water repellent impregnation
- Protection against: Chloride ions
- Uses: Used in areas to prevent the ingress of water borne contaminants like chloride ions. Not to be used in areas subject to hydrostatic pressure
- Protection mechanism: Hydrophobic pore liner

A silane and silane/siloxane combination has been chosen for use in this work. Essentially, both provide the same mechanism of protection but, pure silanes are able to penetrate deeper into concrete substrates due to their small molecules. However, small molecules are also responsible for the volatility of silanes. For this reason, silanes and siloxanes are often combined to form materials that are less volatile but are still able to penetrate concrete to depths greater than siloxanes. Silane/siloxane materials are able to penetrate deeper into concrete due to the small silane molecules while the larger siloxane molecules ensure that evaporation is reduced so that full polymerisation and cross linking occurs (Thomas, 2002).

3.3 Preparation of concrete specimens

Concrete produced under site conditions is often of insufficient quality. Material selection and mix design are important and required for good quality concrete, but poor placing, compaction and curing are often to blame for premature deterioration caused by corrosion. It was the aim of this work to produce poor quality concrete that would fail under the specifications outlined in the South African durability index approach.

A single mix design was used in this work to produce all of the samples required for testing. Due to the number of samples required, concrete had to be produced in four separate batches. To ensure uniformity of the batches; mix proportions, mixing times, compaction times, curing times and curing conditions were strictly controlled. Initially, a number of trial mixes were produced in the laboratory but none of these mixes produced concrete that failed to meet specifications outlined by the South African durability index approach. Preliminary oxygen permeability and chloride conductivity values were found to be in acceptable ranges as outlined by the South African durability approach as discussed in Section 3.3. In other words, poor quality concrete could not be produced under normal laboratory conditions. It was decided that poor site conditions should be reproduced in the laboratory to obtain the desired results. However, to ensure consistency of the batches, mixing and compaction had to be kept constant. Thus in order to produce concrete which would fail to meet requirements outlined in the South African durability approach, specimens were demoulded and placed in an oven at 50°C for 4½ hours which had the effect of replicating poor site conditions. The degree of hydration and hence durability is influenced by early age curing. Good curing practices are necessary to ensure good quality cover concrete which is primarily responsible for protection against the ingress of corrosion causing agents (Ballim and Basson 2001). Fly ash was used in this mix to promote later age strength development as it was found that oven drying greatly reduced the strength of plain CEM I mixes. The mix specifications used in this work are summarised as follows:

Table 3.1: Mix specifications

Binder type:	70% CEM I : 30% Fly ash
Mass of binder:	270 kg
Mass of water:	180 kg
Mass of aggregate: (13 mm Greywacke)	1150 kg
Mass of sand: (Klipheuwel)	840 kg
Slump:	190 mm
Water:binder ratio:	0.67
Curing regime:	• Demoulded after 24 hours • Placed in 50°C oven for 4½ hours • Left in the laboratory for 28 days (23 ± 2°C, 65 ± 5% RH)

A number of differently sized samples were required for the testing carried out in this work. Samples required for strength were cast from 100 x 100 x 100 mm cubes as specified by SANS 5863, 2006. Durability samples were cut and prepared from larger 200 x 200 x 200 mm cubes. Due to the large quantity of samples required for testing, samples required for carbonation, modified bulk diffusion, chloride conductivity and adhesion/microscopy were prepared from larger 500 x 100 x 100 mm concrete beams.

Table 3.2: Summary of sample sizes required for testing

Test type	Sample dimensions
Strength	100 x 100 x 100 mm (cubes)
Oxygen permeability index	70 mm diameter x 30 mm height (discs)
Water sorptivity	70 mm diameter x 30 mm height (discs)
Chloride conductivity	70 mm diameter x 30 mm height (discs)
Carbonation	50 x 50 x 100 mm (square prisms)
Modified bulk diffusion	70 mm diameter x 75 mm height (cylinders)
Chloride spray	70 mm diameter x 75 mm height (cylinders)
Adhesion/microscopy	70 x 70 x 40 mm (square prisms)

3.3.1 Determination of strength

The cube strength of each concrete batch was determined in accordance with SANS 5863, 2006. 100 x 100 x 100 mm cubes were sampled at 28 days and the strength of each batch was determined by averaging the results from three samples (SANS 5863, 2006).

3.3.2 Determination of South African durability indices

Durability indices for each of the concrete batches produced were determined in accordance with the South African Durability Index Manual 1999. A brief description of the test methods, measurable parameters and calculations follows (Alexander et al, 1999):

Oxygen permeability index

Concrete discs (diameter 30 mm and thickness 70 mm) were prepared in the laboratory and placed in an oven set to 50°C for a period of seven days after which they are allowed to cool for 2 hours in a desiccator. The samples were placed into the testing cells which were then pressurised with pure oxygen to 100 ± 5 kPa. The pressure in the cell was recorded with a data logger for a period of 6 hours or until the pressure dropped below 50 ± 2.5 kPa.

The data collected during the test was used to calculate a D'Arcy coefficient of permeability for each sample given by:

$$k = \frac{\omega V g d z}{R A \phi}$$

Where:
- k = coefficient of permeability of test specimen (m/s)
- ω = molecular mass of oxygen (32 g/mol)
- V = volume of oxygen in the test cell (m^3)
- g = acceleration due to gravity (9.81 m/s^2)
- d = average specimen thickness (m)
- z = slope of the regression line obtained by plotting measured and predicted values of pressure
- R = universal gas constant (8.313 Nm/K mol)
- A = cross-sectional area of the test specimen (m^2)
- φ = temperature (K)

The OPI for the batch of concrete was calculated using the D'Arcy coefficients from each sample:

$$OPI = -\log_{10}\left[\tfrac{1}{4}(k_1 + k_2 + k_3 + k_4)\right]$$

Where:
- OPI = oxygen permeability index
- k_n = coefficient of permeability of each test specimen (k_1 - k_4)

Water sorptivity

The water sorptivity test was performed on the same samples used in the OPI test. The circumference of the disc was covered with tape to ensure a watertight seal. The samples were then placed into a tray containing sheets of paper towel saturated in a calcium hydroxide solution. The mass of the samples was measured at regular intervals for 25 minutes. The samples were then moved to a tank were they were placed under dry and fully submerged (saturated) vacuum conditions (-75 kPa) for 3 hours and 1 hour respectively. Fully

submerged vacuum conditions refer to complete immersion, such that the 5 mol calcium hydroxide solution level is approximately 40 mm above the samples. At this point, the vacuum was released and samples were left to soak in the solution for a further 18 hours. Finally, the saturated mass of the samples was measured.

The mass gain of water at each measurement interval was plotted against the square root of time and a best-fit line is obtained from the plot. Water sorptivity was then calculated from the gradient of the best-fit line:

$$S = \frac{Fd}{M_{SV} - M_{S0}}$$

Where: S = sorptivity of the specimen (mm/√hour)
F = slope of the best-fit line from plotting M_{WT} against √t (g/√hour)
d = average specimen thickness (mm)
M_{SV} = vacuum saturated mass of the specimen (g)
M_{S0} = dry mass of the specimen at the beginning of the test (g)

Chloride conductivity

Samples for the chloride conductivity are prepared in a similar manner as those used for the OPI and sorptivity tests. After 7 days of oven drying at 50°C, the samples were placed in a tank where they were subjected to dry and fully submerged (saturated) vacuum conditions (-75 kPa) for 3 hours and 1 hour respectively. At this point, the vacuum was released and the samples are left to soak in the 5 mol sodium chloride solution for a further 18 hours. A test cell was then used to apply a potential difference of approximately 10 volts across the sample. Outputs of current (mA) and voltage (V) were recorded for each sample and used to calculate the chloride conductivity:

$$\sigma = \frac{it}{VA}$$

Where: σ = conductivity of the specimen (mS/cm)
i = current (mA)
t = average thickness of the specimen (cm)
V = voltage difference (V)
A = cross-sectional area of the specimen (cm^2)

Additionally, the porosity of the samples is calculated:

$$n = \frac{M_S - M_D}{At\rho_S}$$

Where: M_S = vacuum saturated mass of the specimen (g)
M_D = dry mass of the specimen at the beginning of the test (g)
A = cross-sectional area of the specimen (mm^2)
t = average thickness of the specimen (mm)
ρ_S = density of sodium chloride solution (1.19×10^{-3} g/mm^3)

3.3.3 Application of protective surface treatments

The test specimens used in this investigation were cut and cored from larger beams as outlined in Section 4.3. Because water was required during the cutting and coring processes, test specimens were dried in the oven for 7 days at 50°C to ensure uniform substrate moisture conditions. With the exception of one face, specimens were sealed using a two-part epoxy resin impervious to gasses and liquids. The protective surface treatment was then applied to the remaining specimen surface in accordance with the manufacturer's guidelines. All of the samples were then left in the laboratory for a minimum of 28 days before testing began to ensure complete curing of each product. A brief summary of the application process is given for each product.

Uncoated (reference samples)

Uncoated samples were used in this investigation in order to obtain a set of reference results for carbonation and chloride ingress (modified bulk diffusion and chloride spray). Reference samples were sealed in the same manner as the coated samples however, the remaining uncoated remained untreated. Additionally, uncoated samples were not exposed to the UV weathering regime due to limited space in the UV weathering chamber. After preparation, uncoated samples were stored in the laboratory (23 ± 2°C, 65 ± 5% RH) until required testing.

Acrylic dispersion

A low-viscosity priming coat was applied to the exposed concrete surface. Two coats of the acrylic dispersion were then applied with the appropriate waiting time between each coat. A spray gun was used to apply the coating to ensure that the application rate of 5 litres per square meter was achieved as accurately as possible.

Acrylic resin

An initial 10% water-diluted priming coat of the product was applied to the concrete surface. The 10% water-diluted priming coat was recommended for absorbent substrates. An additional two coats of the product were subsequently applied to the specimens using a spray gun to achieve the required spread rate. The required waiting time between coats was observed.

Cement based

No primer was required for the polymer modified cementitious rendering. The product was applied in two layers of approximately 1 mm each. The recommended waiting period was observed before the application of the second layer. The layers were applied in orthogonal directions using a brush.

Cement based FR

No primer was required prior to the application of the fibre reinforced cementitious rendering. The product was applied in three layers, each approximately 1 mm thick. Each layer was applied at right angles to the previous layer after the recommended waiting time. The rendering was applied with a brush to obtain a total thickness of approximately 3 mm.

Silane/siloxane

The silane/siloxane was applied in three coats using a low-pressure spray gun to ensure the correct spread rate. Each coat was applied wet on wet to ensure maximum penetration. A priming material was not required prior to the application of the silane/siloxane.

Pure silane

The pure silane impregnation was applied wet on wet in two consecutive coats. There was no need for the application of a priming material. A low-pressure spray gun was used to achieve the correct spread rate and ensure even penetration into the concrete surface.

3.3.4 UV weathering regime

Some of the highest values of solar radiation have been recorded in Southern Africa (de Jong, 1973). Much of the solar radiation received at the Earth's surface is in the form of infrared and the visible light spectrum (Q-Lab Products, 1994). UV is the invisible spectrum (295 - 400 nm) of solar radiation primarily responsible for altering the chemical composition of materials through photon absorption (supplied from high doses of UV radiation). Free radicals produced from the parent material due photon absorption chemically react in the presence of air (oxidation) and subsequent aging and damage to materials occurs (Woo et al, 2008).

A weathering chamber was used to simulate the harsh South African UV exposure conditions. The chamber provided fully automated UV exposure combined with hot/cold and wet/dry cycles. UVA 340 fluorescent bulbs were used to simulate the solar wavelength region of 295 - 365 nm (with maximum output at 340 nm). At this point, it should be noted that artificial weathering produces highly varied results that should be evaluated on a comparative basis only. In other words, it is difficult to equate natural and artificial weathering because outdoor exposure conditions vary and are unpredictable. For this reason, rules-of-thumb based on geographical location and material type are used to estimate the number of hours required to simulate natural weathering conditions in a UV chamber. Based on the knowledge and experience of a local expert it has been estimated that approximately 4000 hours accelerated weathering (2666 hours UV exposure, 1333 hours condensation) is required to simulate ±9 years of weathering for the Western Cape area (Roediger, 2009). In other studies, attempts have been made to calculate equivalence factors between natural and artificial weathering using specific exposure conditions. Using local exposure conditions, one can calculate an equivalence factor for much of Southern Africa in a similar manner (Martin, 2005). A horizontal surface in Southern Africa receives an average solar irradiance of approximately 7000 MJ/m^2/year (SARERD, 1999). It is estimated that approximately 0.5% of the total radiation received at the surface is in the UV spectrum, therefore (Martin, 2005; Grossman, 1977):

$0.5\% \times 7000\ MJ/m^2/year = 35\ MJ/m^2/year$

By calculating the area under the output curve for UVA 340 fluorescent bulbs, the irradiance produced by the UV weathering chamber is estimated to be 33 W/m^2 or 0.12 $MJ/m^2/hour$. Thus, an equivalence factor can now be calculated:

$$\frac{35\ MJ/m^2/year}{0.12\ MJ/m^2/hour} = 292 \text{ hours accelerated UV exposure/year natural exposure}$$

In other words, 292 hours of accelerated UV exposure is required to simulate 1 year of natural UV exposure or 2628 hours for 9 years. In this investigation, samples remained in the weathering chamber for a total of ±4000 hours (total time including condensation cycles). The weathering regime for coatings is recommended by ASTM G154-06 (Standard practice for operating fluorescent light apparatus for UV exposure of non metallic materials). High surface temperatures and condensation cycles are specified in ASTM G154-06 as part of the combined effect of heat and moisture changes on the weathering of coatings. Temperature control within the QUV weathering chamber was achieved with the use of a thermometer mounted in the same position as the exposed samples. As per the instruction manual, calibration of the QUV weathering chamber was carried out prior to use and at regular intervals during exposure. The exposure regime used in this investigation was as follows (ASTM G154-06, 2006):

Figure 3.1: QUV chamber used to simulate UV weathering conditions

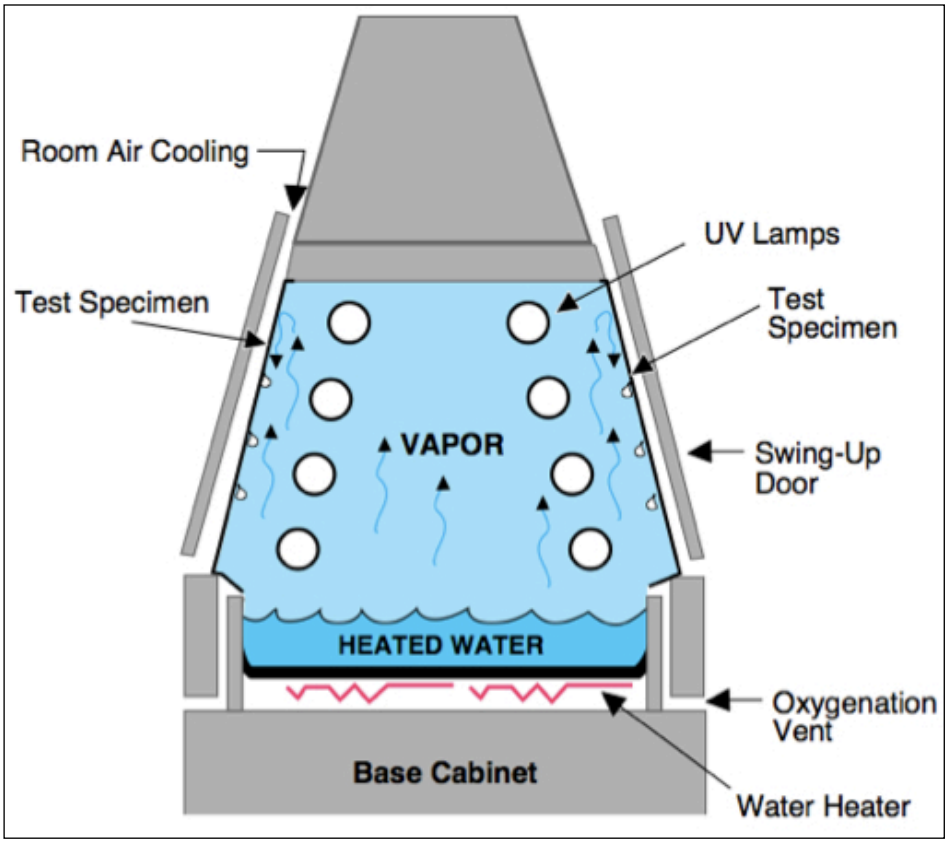

Figure 3.2: Section showing layout of QUV weathering chamber

- 8 hours exposure to UVA 340 fluorescent light at 60 ± 3°C
- 4 hours condensation at 50 ± 3°C (no exposure to UV, formation of moisture drops on samples)

For each 24 hour period, samples were subject to 16 hours (two thirds of the total time) UV expose at 60°C and 8 hours (one third of the total time) condensation at 50°C. Thus 4000 hours weathering time consists of a total of 2666 hours UV exposure and 1333 hours condensation. These exposure values agree closely with the values obtained from Roediger (2009) and Martin (2005).

3.4 Testing of concrete surface treatments

3.4.1 Carbonation

Prior to placement in the carbonation chamber, samples were placed in an oven at 50°C for a period of 7 days. Preconditioning was carried out to ensure that samples had approximately the same moisture content before carbonation testing could begin. Moisture and gas diffusion properties vary for different coatings (und uncoated concrete) thus allowing varying amounts of moisture and gas to enter or leave concrete. To verify that samples had approximately the same moisture content, the masses of samples was recorded (0.01 g precision) prior to UV exposure, after UV exposure and finally after preconditioning.

Coated and uncoated (reference) samples (50 x 50 x 100 mm) were placed in a controlled carbon dioxide environment. A Leec research CO_2 incubator was used to maintain the following constant atmospheric conditions:

- Carbon dioxide level: 5%
- Relative humidity: 70 ± 5%
- Temperature: 32 ± 2°C

Literature has suggested that maximum carbonation is likely to occur at approximately 75% relative humidity. Additionally, the carbon dioxide level of 5% was chosen to ensure the existence of a large concentration gradient and thus an accelerated rate of carbonation (Roy et al, 1998; Richardson, 2002).

Coated samples remained in the carbonation chamber for a period of 125 days. During this period, the carbonation depth was measured and recorded at 0, 23, 55 and 125 day intervals. Uncoated samples remained in the chamber for 55 days in which time the carbonation depth was measured at 0, 10, 23 and 55 days. Near complete carbonation occurred after 55 days. At each test interval, 10 mm layers were sliced off the prism and sprayed with a phenolphthalein solution to obtain a colour change in the carbonated portion of the sample (i.e. pink in the uncarbonated region to colourless in the carbonated material). The cut faces of the sample remains were then resealed and placed back in the carbonation chamber. Figures 4.3 and 4.4 show the cut faces with applied phenolphthalein. Uncarbonated concrete appears as pink areas while carbonated concrete experiences no colour change. Note the difference in carbonation depth between different testing ages.

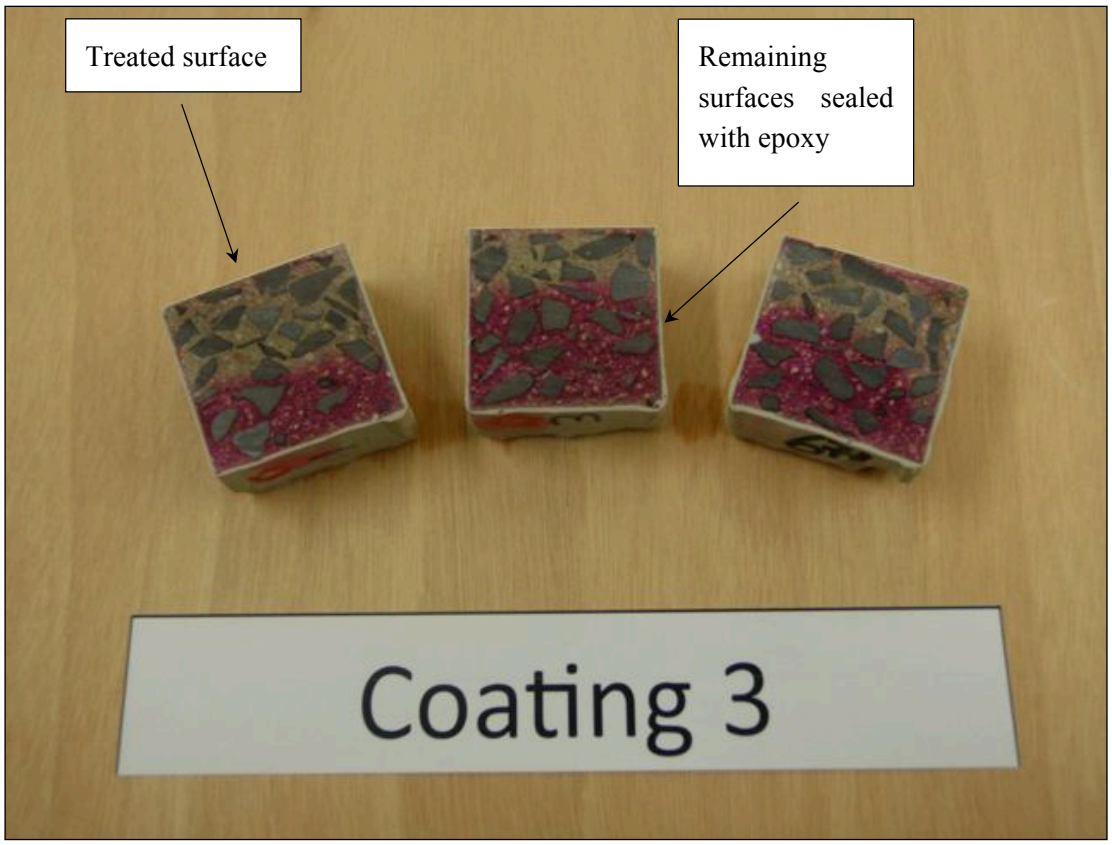

Figure 3.3: Example of carbonation testing after 23 days

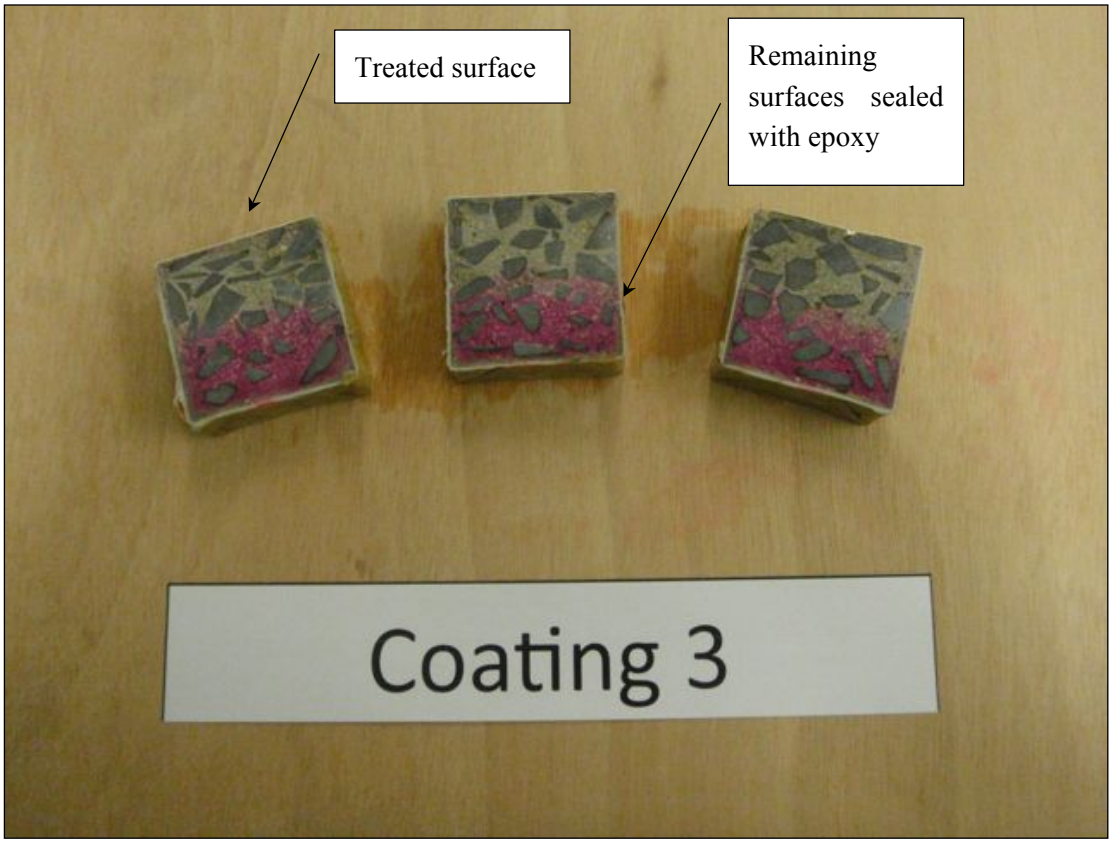

Figure 3.4: Example of carbonation testing after 55 days

3.4.2 Modified bulk diffusion test

The chloride conductivity (South African Durability approach) is linked to the chloride diffusivity of concrete (Alexander and du Preez, 2004). The chloride diffusion coefficient is obtained from the bulk diffusion test. An outline of ASTM C1556-04 (Standard test method for determining the apparent chloride diffusion coefficient of cementitious mixtures by bulk diffusion) is summarised. Cylindrical concrete samples (70 mm diameter, 75 mm height) are sealed using a waterproof epoxy. A single face is left exposed such that chloride ions in solution are able to penetrate the concrete from one direction. Samples are preconditioned by

saturation in a calcium hydroxide solution. After preconditioning, samples are rinsed with fresh water and placed into a bath containing 2.8 mol/l sodium chloride solution for a period of at least 35 days. Samples are then removed and readied for grinding. Depending on the concrete composition, differing layers of the sample ground off to differing depths and collected for analysis. The acid-soluble chloride-ion content of each layer is then obtained. The diffusion coefficient for the concrete sample can then be calculated from the acid-soluble chloride-ion content for each layer.

In the bulk diffusion method outlined by ASTM C1566-04, samples are saturated in a calcium hydroxide solution prior to placement in the sodium chloride solution. However, surface treatments used to prevent the ingress of chloride ions do not allow the ingress of water thus, preconditioning of samples in a calcium hydroxide solution was not possible. Rather, samples were placed directly into the 2.8 mol/l sodium chloride solution for a period of 42 days. Therefore, calculation of a diffusion coefficient was not possible for the test

samples. Rather, data was used to assess the protective properties of the coatings based on a comparison to the uncoated samples. Prior to placement in the sodium chloride solution, samples were placed in an oven at 50°C for a period of 7 days. Sample masses were recorded prior to weathering, after weathering and after preconditioning in the oven to verify that significant amounts of moisture had not been absorbed by the samples. Testing was carried out on unweathered, 3, 6 and 9 years equivalent weathering samples. Test data from coated samples was compared to data obtained from control samples.

3.4.3 Chloride spray

Surface treatments are used to protect concrete structures in the harsh marine environment. The worst degradation of concrete is found in the tidal and splash/spray zones of a marine environment; thus, it was considered useful to evaluate coatings under the same conditions. Prior to placement in the sodium chloride solution, samples were placed in an oven at 50°C for a period of 7 days. Sample masses were recorded prior to weathering, after weathering and after preconditioning in the oven to verify that significant amounts of moisture had not been absorbed by the samples. Testing was carried out on unweathered, 3, 6 and 9 years equivalent weathering samples. Test data from coated samples was compared to data obtained from control samples

A custom built chamber was used to simulate the splash/spray zone by spraying samples with a 2.8 mol/l sodium chloride solution (±25°C - temperature of water in laboratory atmosphere) for 30 minutes followed by a drying time of 2 hours at ±60°C. The exposure temperature was chosen to be in keeping with the maximum temperature recommended during UV exposure. Additionally, the sodium chloride solution was chosen to be the same as that used in the modified bulk diffusion test (2.8 mol/l). The changes in temperature were used to simulate effects caused by sudden changes in temperature (thermal shock). Due to limitations of this work, it was not possible to assess chloride penetration of the tidal zone in the marine environment.

3.4.4 Adhesion

The adhesion of the surface coatings to the concrete substrate was evaluated at each weathering interval. The pull-off test was performed by securing a loading dolly (50 mm diameter) perpendicular to the surface of the coating with an adhesive. After sufficient curing time had elapsed, the dolly was placed into the Zwick load actuator and aligned with a steel box section so that the applied force was normal to the testing surface. The test arrangement can be seen in Figure 3.5. The failure type was described according to the surface along which failure occurred and the pull off strength calculated from the maximum recorded load and surface area of the dolly (ASTM D4541-02, 2002).

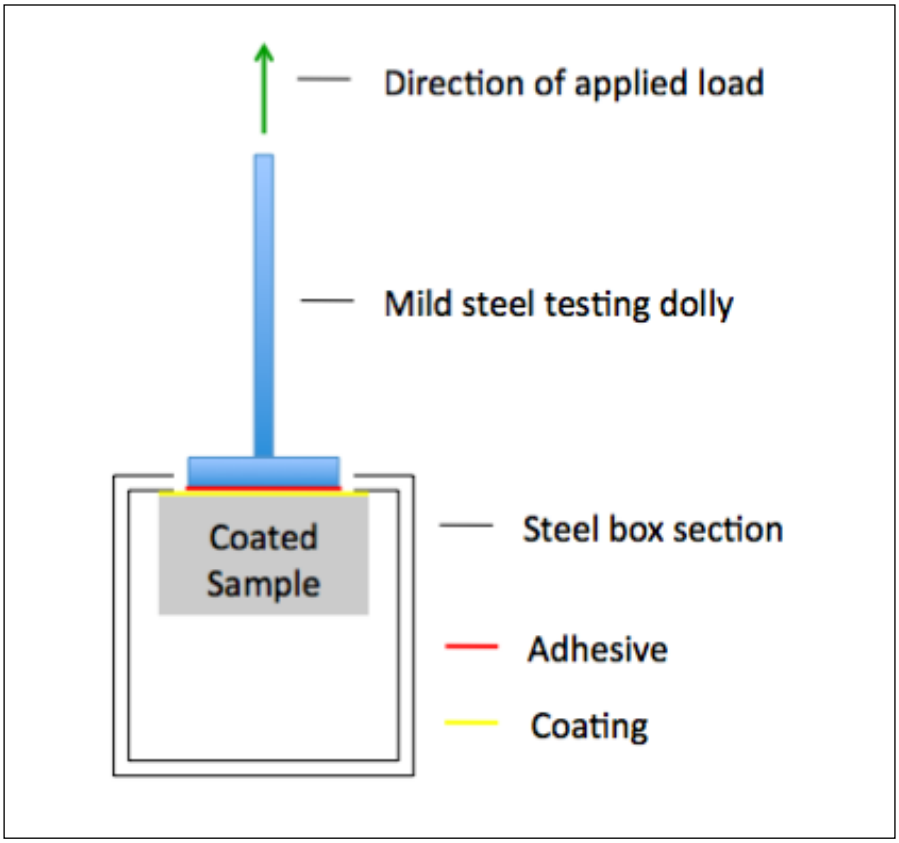

Figure 3.5: Schematic of adhesion test setup

3.4.5 Impregnation depth of penetrating surface treatments

The impregnation depth of the pure silane and siloxane surface treatments was estimated by spraying a cross section of the specimen with water. Due to the hydrophobic nature of the surface treatments, water is repelled in the area treated with the products. A clearly impregnated region is visible to the naked eye and can easily be measured (McCarter, 1996).

3.4.6 Summary of sample testing

Table 4.3 summarises the testing and exposure carried out for both coated and uncoated samples. A tick has been placed in the relevant box if a certain test has been carried out. In this work, surface treatments were chosen on the basis that they prevent the ingress of carbon dioxide and (or) chloride ions. Additionally, the protection mechanism is different for each of the surface treatments evaluated in this work. Therefore, only tests relevant to the properties of each surface treatment were evaluated.

Table 3.3: Summary table of testing performed

Concrete or product tested	Test/exposure								
	OPI	CC	Sorptivity	Strength	UV exposure	Carbonation	Chloride ingress	Chloride spray	Adhesion
Uncoated Concrete	✓	✓	✓	✓		✓	✓	✓	
Acrylic dispersion					✓	✓			✓
Acrylic resin					✓	✓			✓
Cement based					✓	✓	✓	✓	✓
Cement based FR					✓	✓	✓	✓	✓
Silane/siloxane					✓		✓	✓	
Pure silane					✓		✓	✓	

3.4.7 Summary of testing schedule

The aim of the experimental program in this work has been to evaluate the effectiveness and longevity of certain generic type coatings in providing protection against the ingress of carbon dioxide and chloride ions. Furthermore, it was the aim of this work to evaluate concrete surface treatments under simulated conditions. Therefore, it was important to recreate (as best as possible) those conditions that would necessitate the need to apply protective products to the surface of concrete structures. The testing programme is summarised in Figure 3.6.

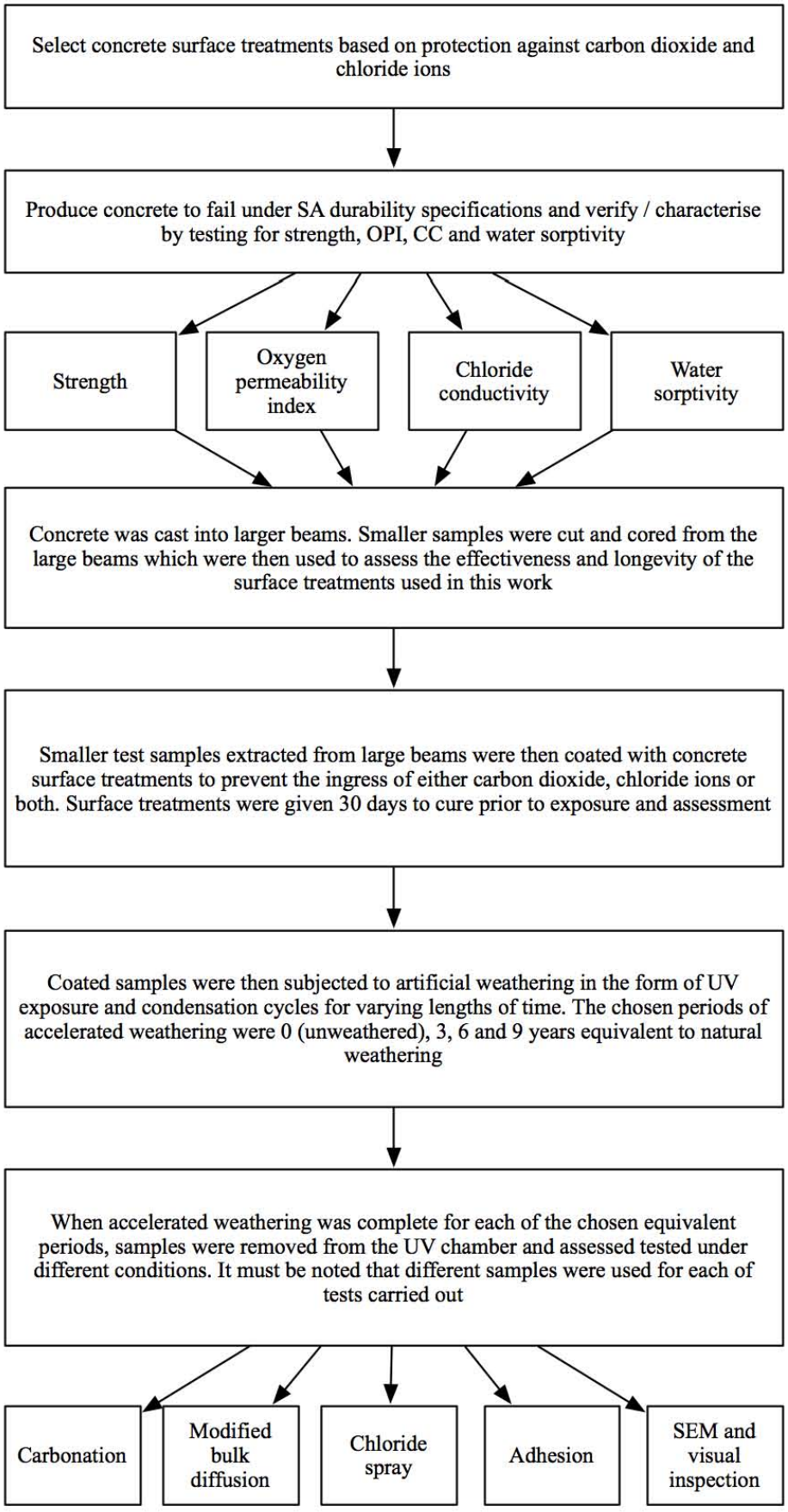

Figure 3.6: Flow chart summarising testing schedule

4 Results

4.1 Mix classification and service life estimation

From the outset, the aim of the laboratory project was to assess surface treatments under simulated natural conditions. This meant starting with poor quality concrete which, under the current South African durability index approach, would fail to meet service life predictions. The results of strength and durability are presented in Table 5.1. Results of individual mixes may be found in Appendix B.

Table 4.1: Summary of strength and durability results used to categorise concrete

Parameter				
Strength (MPa)	**OPI (Unit less)**	**Sorptivity (mm/√hr)**	**CC (mS/cm)**	**Porosity (%)**
15.2	9.06	21.6	3.99	12.6

The durability values obtained from the laboratory tests are used to estimate the service life of a concrete structure exposed to conditions specified in the associated models. To err on the side of caution, worst-case scenarios for carbonation and chloride ingress have been assumed. Additionally, service life estimates from the carbonation model have been made for assumed cover depths of 30, 40 and 50 mm while a minimum cover depth of 50 mm has been assumed for the chloride ingress model.

Oxygen permeability index

Input parameters	OPI value from laboratory test:	±9.06
	Relative humidity:	60%
	Fly ash content of total binder:	30%

Service life estimates	Carbonation depth (30 mm):	Reached after ±10 years
	Carbonation depth (40 mm):	Reached after ±25 years
	Carbonation depth (50 mm):	Reached after ±40 years

Chloride conductivity

Input parameters	CC value from laboratory test: Exposure conditions: Fly ash content of total binder:	±3.99 mS/cm Splash/spray zone 30%

Service life estimate	Chlorides by mass of binder (50 mm):	±2.84% (<1 year)

Ordinarily, engineers would reject concrete produced to these specifications. However, there are occasions when outright rejection of the concrete in question is not possible. From a practical standpoint corrosion will commence after a fraction of the required service life. Thus, remedial measures such as the application of surface treatments are implemented by engineers to prevent the onset of corrosion and hence extend service life estimates.

4.2 Carbonation

4.2.1 Results of carbonation exposure

Uncoated samples

The mean depth of carbonation has been plotted for uncoated concrete in Figure 5.1. Full results and individual carbonation curves for different mixes are presented in Appendix B. Near complete carbonation was achieved after only 55 days with a depth of approximately 49 mm. Thus, no further testing was carried out on the uncoated carbonation samples. The carbonation curve from uncoated concrete samples is plotted in Figures 5.2 to 5.5 together with carbonation curves from the coated samples.

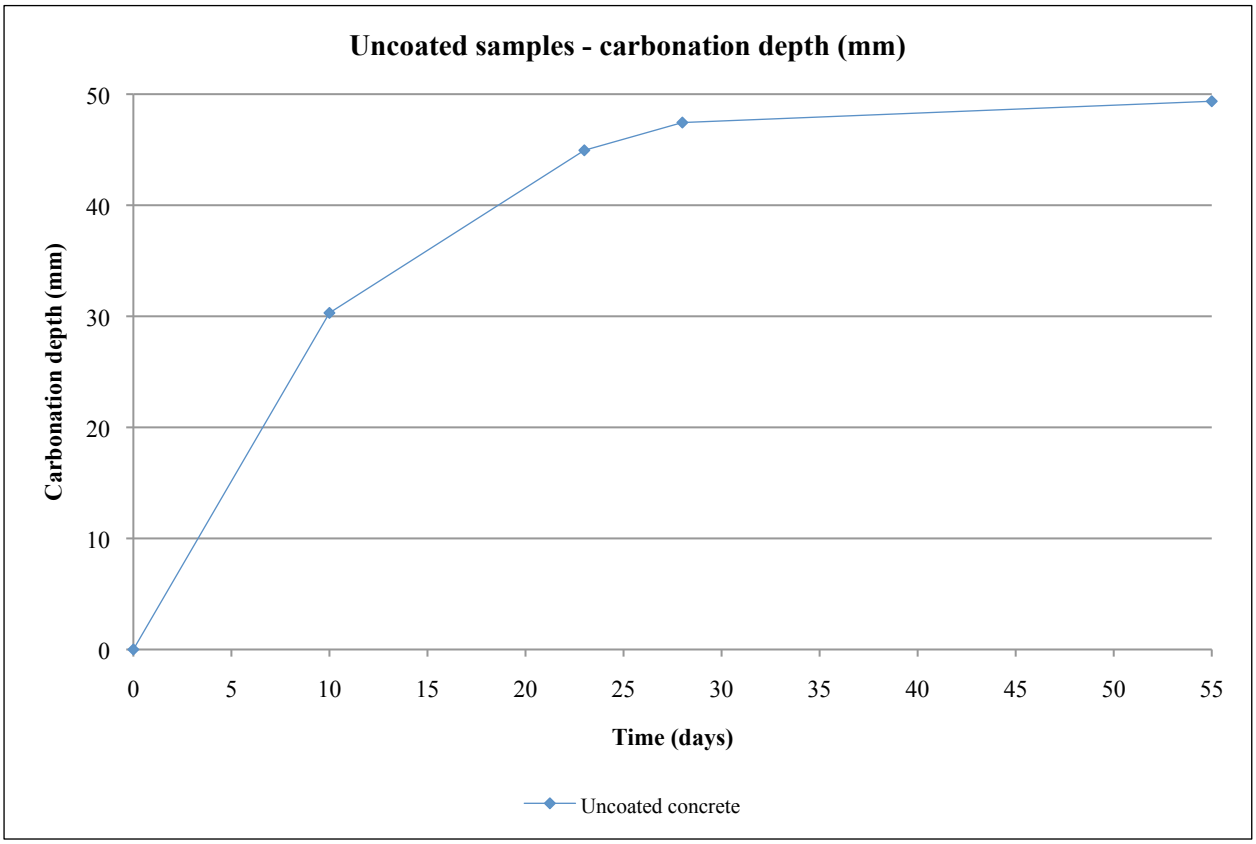

Figure 4.1: Carbonation depth of uncoated samples

Acrylic dispersion

The carbonation curves for the acrylic dispersion at different weathering ages can be seen in Figure 5.2. No visible signs of damage could be observed on the coatings after UV exposure. After 125 days, the unweathered samples experienced carbonation of approximately 16 mm. Samples weathered for an equivalent of 9 years only experienced carbonation of approximately 1 mm. The trend of the data indicates an improvement of the carbonation resistance after exposure to the weathering regime. Overall, carbonation was reduced when compared to the uncoated samples.

The acrylic dispersion is has been classified as a UV curing coating according to product literature. The chemistry of UV curing systems is vast and without knowing specific product information is not possible to determine. The underlying principals however are similar for the UV curing generic group of coatings. Shortwave radiation photons react with the coating to cause the formation of long chain molecules (Schwalm, 2007). Therefore, the improvement of carbonation resistance after UV exposure would agree with improved coating properties outlined in literature.

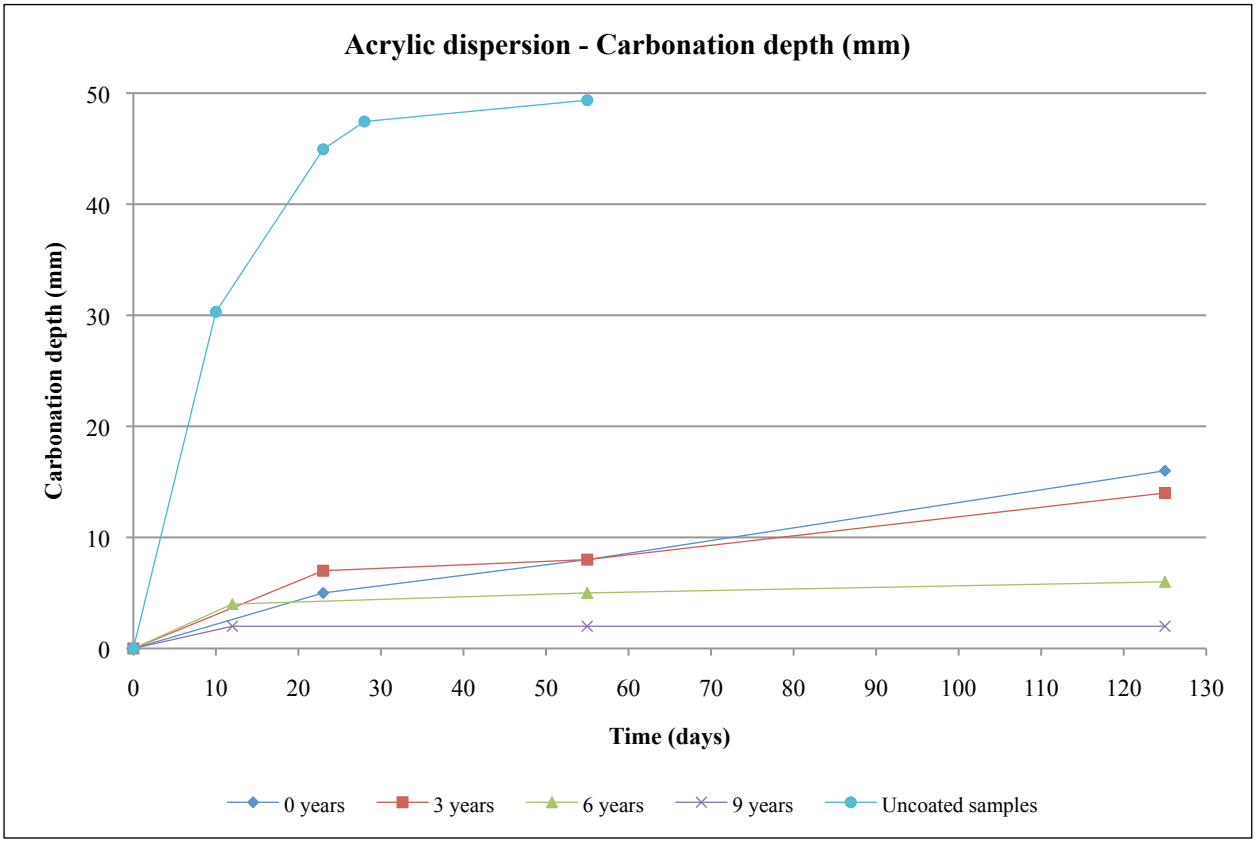

Figure 4.2: Carbonation depth of coated samples - acrylic dispersion

Acrylic resin

An overall improvement of carbonation resistance was observed for the acrylic dispersion in Figure 5.3. No visible signs of damage to the coating were observed after the weathering regime. The data trend indicates an improvement in performance for longer durations of weathering. The unweathered samples experienced the most carbonation of approximately 35 mm while the 9 year equivalent samples experienced approximately 6 mm of carbonation. Based on the results, it seems the UV exposure has had some influence on improving the carbonation resistance of the acrylic resin after weathering however this was unexpected and cannot be explained.

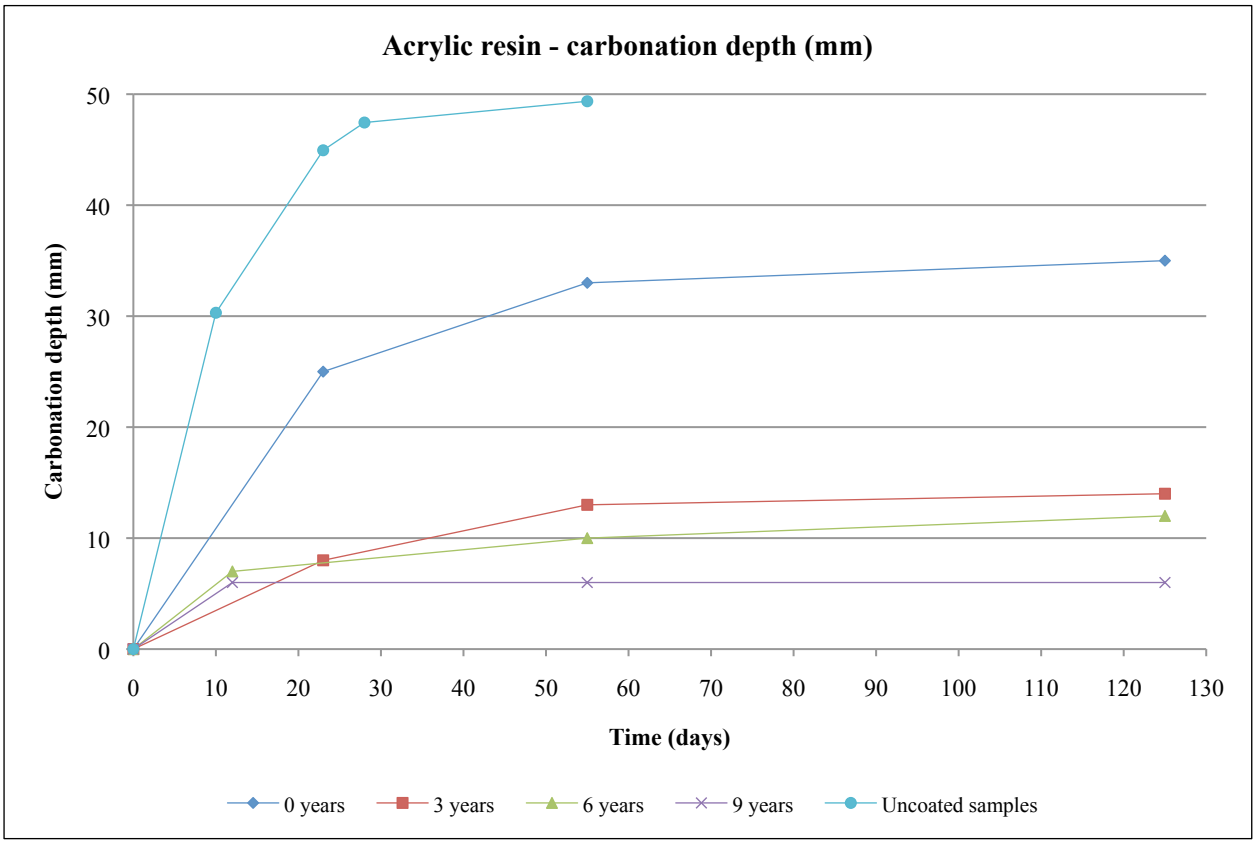

Figure 4.3: Carbonation depth of coated samples - acrylic resin

Cement based

In Figure 5.4, it can be seen that the carbonation resistance of the cement based coating improved with longer durations of weathering. Other than some white superficial surface staining and chalking the cement based coating showed no obvious signs of damaged caused by exposure in the UV chamber. The unweathered samples experienced carbonation of approximately 33 mm while the 9 year equivalent weathered samples experienced only 10 mm. The 6 year equivalent weathered samples experienced less carbonation (6 mm) than the 9 year samples however this is not considered a significant improvement to suggest that extended weathering has caused improved performance of the coating.

Improved performance of the cement based coatings after longer periods of weathering could be accredited to longer and hence improved hydration of the cement based coating at higher temperatures experienced in the weathering chamber. Additionally, moisture was present during weathering which could also contribute to improved hydration of the cement based coating.

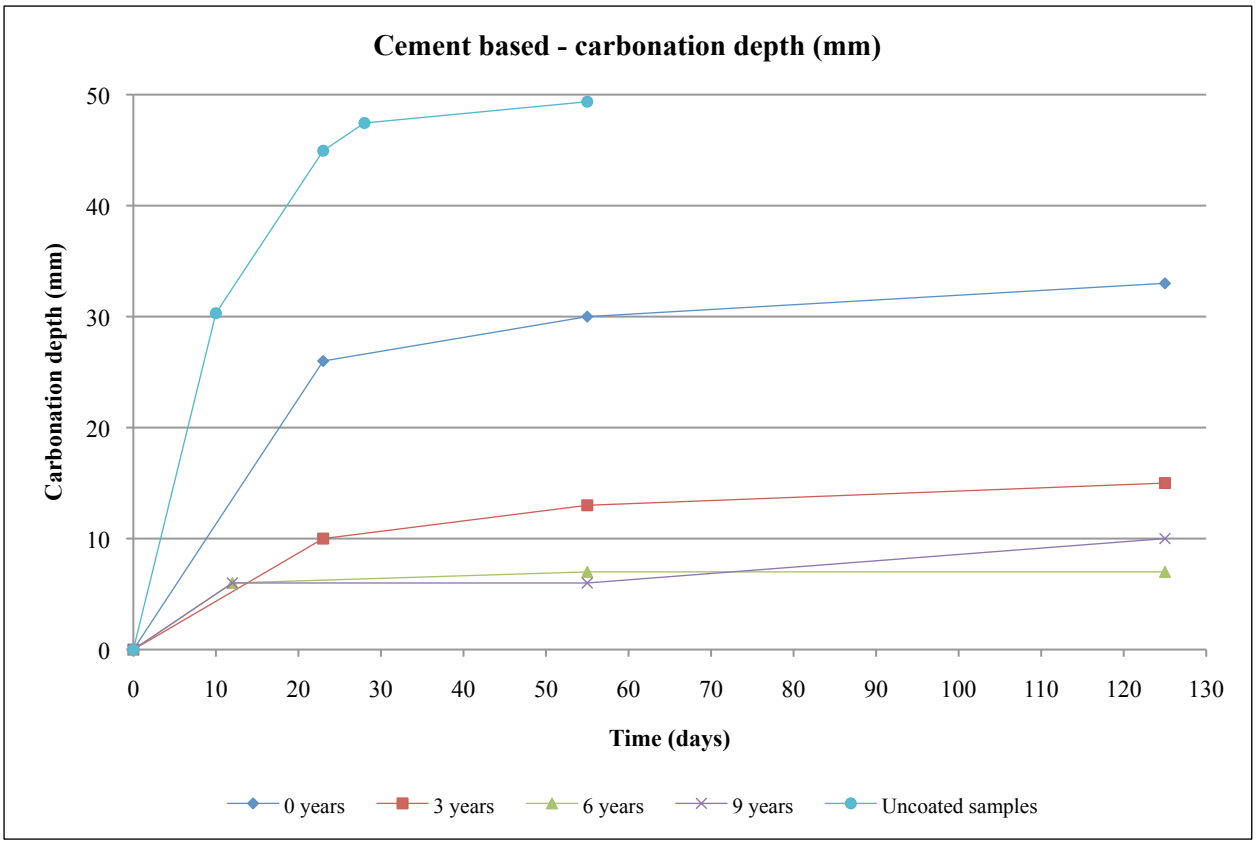

Figure 4.4: Carbonation depth of coated samples - cement based

Cement based FR

Figure 5.5 shows an improvement in carbonation resistance of samples coated with the cement based fibre reinforced coating. Apart from some chalking on the surface of the cement based fibre reinforced coating on removal from the UV chamber, no signs of damage were visible. The maximum carbonation depth after 125 days was approximately 11 mm for the unweathered samples. The 9 year equivalent weathered samples experienced approximately 3 mm carbonation after 125 days. The performance of the coating was seen to improve with longer periods of weathering. Carbonation resistance was see to significantly improve for all coating weathering ages.

Improved performance of the cement based fibre reinforced coating could be accredited to improved hydration of the cement caused by higher temperatures and moist environment of the weathering chamber.

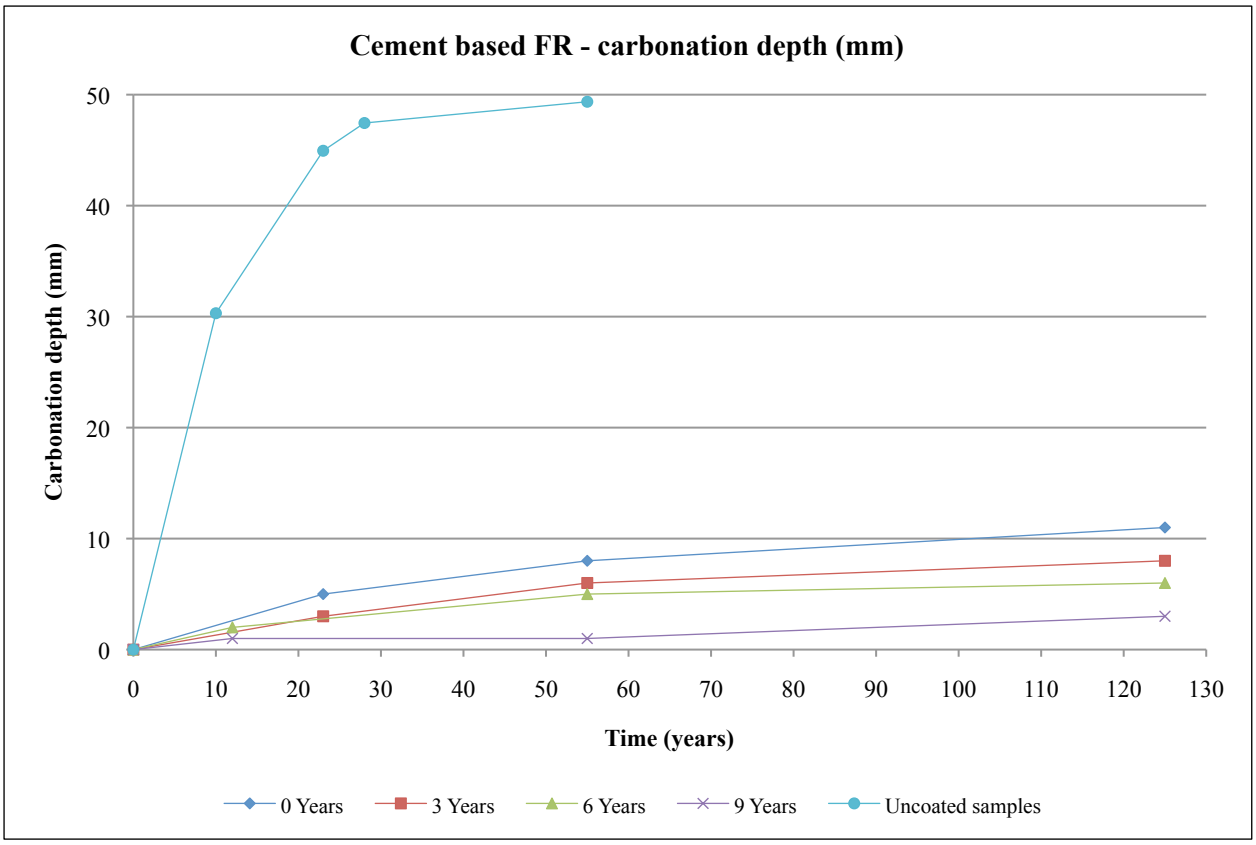

Figure 4.5: Carbonation depth of coated samples - cement based FR

4.2.2 Equivalence of accelerated and natural carbonation

Papadakis et al has suggested a simple method of correlating accelerated and natural carbonation (Papadakis et al, 1989). Carbonation is modelled according to the widely accepted relationship (as discussed in Chapter 3.2.4):

$$x_c = A\sqrt{t}$$

Where: x_c = carbonation depth
A = measure of concrete quality or carbonation constant
t = time

The model provides highly repeatable results under controlled laboratory conditions which for the purpose of this work will suffice. Deviations from the model have been observed in outdoor tests caused by changes in the relative humidity which can affect the carbonation constant. Even under accelerated conditions, where much higher concentrations of carbon dioxide are encountered, the model is valid (Papadakis et al, 1989).

Papadakis et al found that ratio of carbon dioxide concentration used in accelerated testing and natural exposure is directly proportional to the time taken to run the test.

$$\frac{t_1}{t_2} = \frac{\rho_A}{\rho_N}$$

Where: t_1 = equivalent natural exposure time (days but converted to years)
t_2 = accelerated exposure time (days)
ρ_N = atmospheric concentration of carbon dioxide (%)
ρ_A = concentration of carbon dioxide in carbonation chamber (%)

Thus, using this relationship, years of natural carbonation can be assessed in a few days. For this work:

Input parameters	Natural carbon dioxide concentration (ρ_N):	0.05%
	Carbonation chamber concentration (ρ_A):	5%
	Length of time in the carbonation chamber (t_2):	55 days

Output parameter	Equivalent natural exposure time:	±15 years

Based on the relationship presented by Papadakis et al, 55 days of accelerated carbonation is equivalent to approximately 15 years of natural carbonation (Papadakis et al, 1989).

4.2.3 Analysis of carbonation results with respect to the SADI approach

From the carbonation exposure results, it can be seen that the carbonation resistance of the original concrete was improved to varying degrees. To varying degrees, coating type and equivalent natural weathering time affected the carbonation resistance of the treated concrete. In order to evaluate the coatings in terms of the SADI approach, it is useful to calculate and equivalent OPI value.

Papadakis et al, 1989, proposed a relationship linking natural and accelerated carbonation. Using this relationship, it can be shown that the accelerated carbonation period of 125 days is equivalent to ±34 years natural exposure. Therefore, analysis of the carbonation performance has been carried out for the time period equivalent to ±34 years natural exposure.

Input Parameters	Natural carbon dioxide concentration (ρ_N):	0.05%
	Carbonation chamber concentration (ρ_A):	5%
	Length of time in the carbonation chamber (t_2):	125 days

Output Parameter	Equivalent natural exposure time:	±34 years

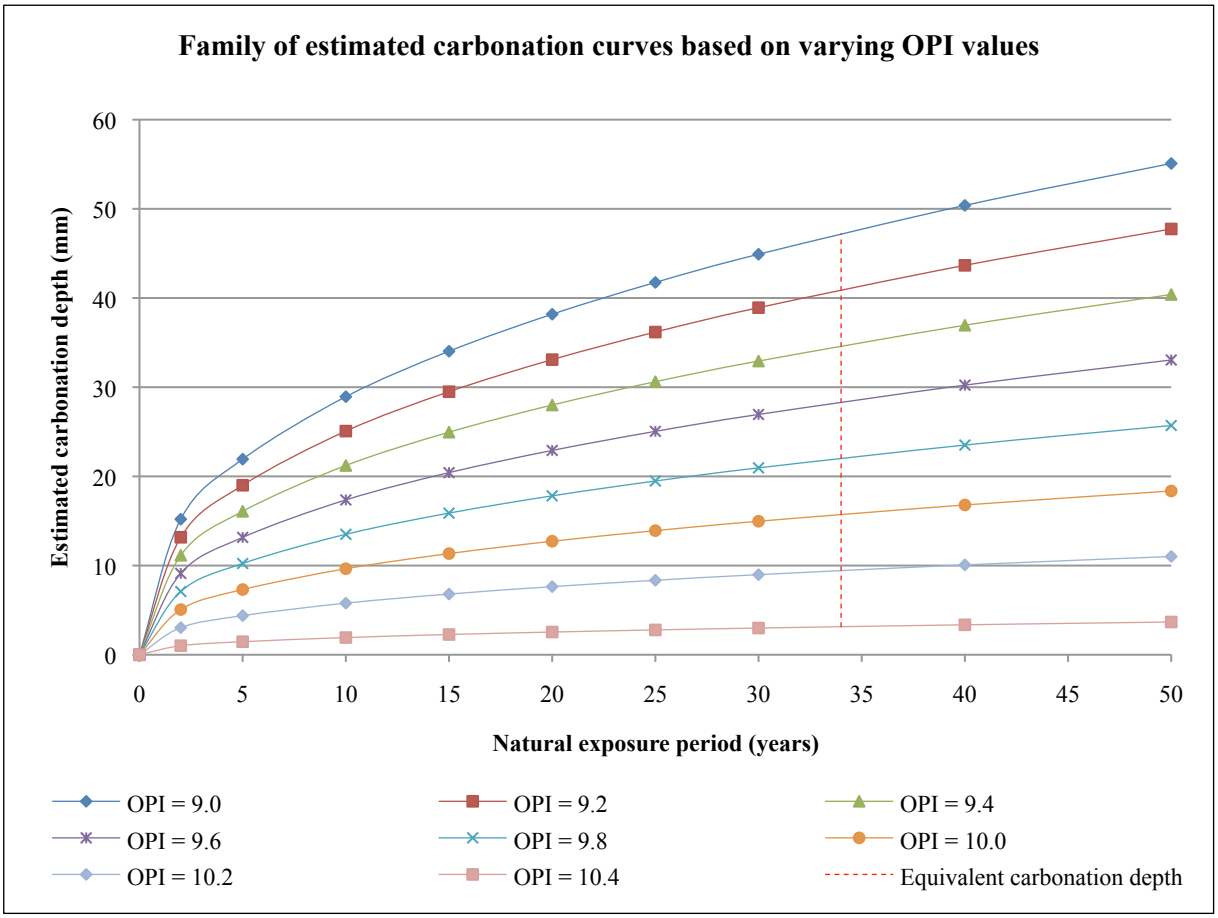

Figure 4.6: Estimated carbonation curves based on changing OPI values

Thus, an OPI value can be calculated for each coating and equivalent natural weathering age since the carbonation depth at 34 years equivalent exposure is known. A family of OPI curves has been plotted in Figure 5.6 based on the same input parameters used in Section 3.3.9. The South African durability index approach uses a model to estimate the carbonation depth (mm) after certain time periods (years) based on a number of input parameters including binder type, measured OPI, and exposure conditions. Since the binder type and exposure conditions remain constant, the OPI is the only parameter affecting the service life. Thus, using the carbonation model, various OPI values have been used to generate the family of curves presented in Figure 5.6.

Based on the carbonation depth observed at an equivalent exposure age of 34 years and Figure 5.6, equivalent OPI values for each coating and equivalent weathering age combination can be obtained. Equivalent OPI values are presented in Table 5.2.

Table 4.2: OPI values for surface treatments and equivalent weathering ages

Surface treatment	Equivalent weathering age			
	0	3	6	9
Acrylic dispersion	10.0	10.0	10.3	10.4
Acrylic resin	9.4	10.0	10.1	10.3
Cement based	9.4	10.0	10.3	10.2
Cement based FR	10.2	10.3	10.3	10.4

It can be seen from Table 5.2 that coatings improved the carbonation resistance of the test specimens in all cases. Concrete used in this work initially had an OPI of 9.0 which was increased to at least 9.4 with the use of concrete surface treatments. Additionally, the weathering process seems to have an effect of the carbonation resistance of each surface treatment. The carbonation resistance is generally improved with longer weathering periods. This could be attributed to improved curing or the concrete or better curing of the surface treatments themselves. The moisture content of the samples has been shown to be similar for all samples after preconditioning and prior to placement in the carbonation chamber. Thus, in service, later age protection could be expected to be much greater than the initial carbonation resistance of the applied surface treatment.

Results and findings from the carbonation testing counter the hypothesis that longer periods of weathering lead to increased material degradation and hence performance reduction of the surface treatments. Table 5.2 provides evidence of improved carbonation resistance with longer periods of weathering. Thus, the improved carbonation resistance could be accredited to one of three conditions; improved surface treatment performance, improved substrate performance or apparent improved substrate performance caused by the presence of pore moisture which could prevent the passage of carbon dioxide. However, the sample mass results presented in Appendix B show no significant change in mass which would prevent the passage of carbon dioxide. The improved carbonation resistance is therefore caused either through extended hydration of the concrete substrate or improved resistance of the coatings during the weathering process.

4.3 Modified bulk diffusion test

Uncoated samples

Figure 5.7 contains the chloride profile for uncoated samples after 42 days exposure. It can be seen that the uncoated concrete had little effect in providing protection against the passage of chloride ions - identifiable by the horizontal chloride profile. The ingress of chloride ions is influenced by two mechanisms - diffusion and convection. Diffusion is the movement of chloride ions governed by the chloride ion concentration gradient of the pore water solution. Alternatively, convection is the movement of pore water (containing chloride ions) caused by the existence of a moisture gradient. Since the samples were not immersed in a calcium hydroxide solution prior to exposure to the sodium chloride solution, the movement of chloride ions through the concrete samples would have been primarily caused by the convection process. Thus, the diffusion process would have had a minor effect in the transport of chloride ions through the concrete samples (Val and Trapper, 2008).

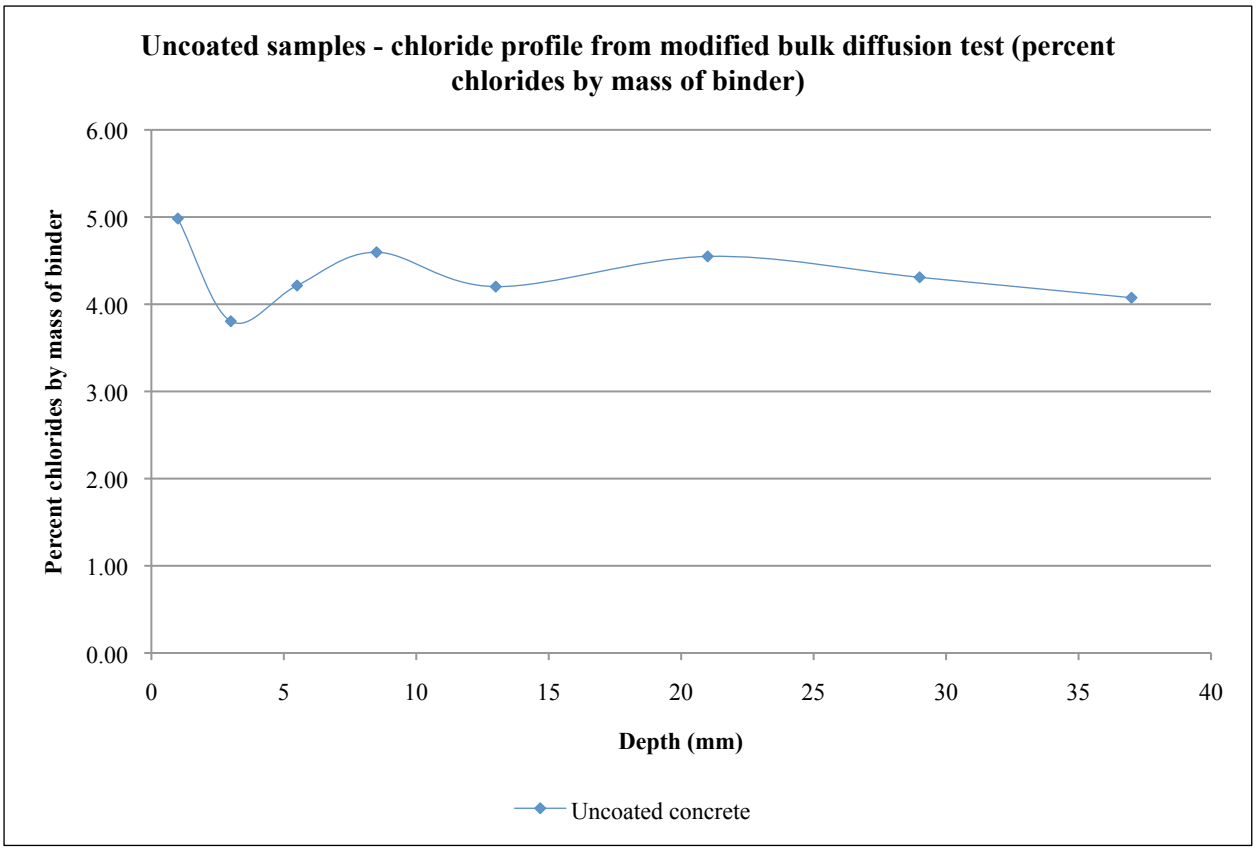

Figure 4.7: Modified bulk diffusion, chloride profile - uncoated samples

The South African durability index approach has already shown the service life to be less that 1 year for uncoated concrete. The results from uncoated concrete samples are plotted in Figures 5.10 to 5.13 along with the test data for coated samples after various equivalent weathering ages. Each data point is an average of 3 samples exposed and tested. In all cases, the coating was removed from the surface prior to evaluation of the chloride profile.

Pure silane

Test data in Figure 5.8 shows a significant reduction in the passage of chloride ions through the unweathered and 3 year equivalent weathered samples. Test results from 6 and 9 year equivalent weathered samples show an unnatural chloride profile. These results suggest that the epoxy coating used to seal the side of the samples has been damaged during the weathering process. Thus, it would appear that chlorides have entered from the sides and migrated through the sample to approximately 10 mm below the surface. The profile seen agrees with the impregnation depth seen in Figure 5.23 which was found to be approximately 10 mm. Therefore, the pure silane surface treatment is effective in reducing the passage of chloride ions and is unaffected by the weathering regime.

Similarly to the silane/siloxane samples, pure silane surface treatments should be ineffective reducing chloride ingress under hydrostatic pressure (Thomas, 2002). In view of the evidence presented in literature, results obtained from the pure silane samples are of interest since the passage of chlorides was significantly reduced. Further investigation into the performance of pure silanes under hydrostatic pressure should be explored.

It must of course be noted that although that pure silane samples exhibit signs of epoxy sealant failure, it is unlikely that damage is limited to only specific samples. Thus it likely that the epoxy used to seal the sides of the samples has been damaged for all samples exposed to 6 and 9 years equivalent weathering. The preceding chloride ingress results should therefore be treated with some caution.

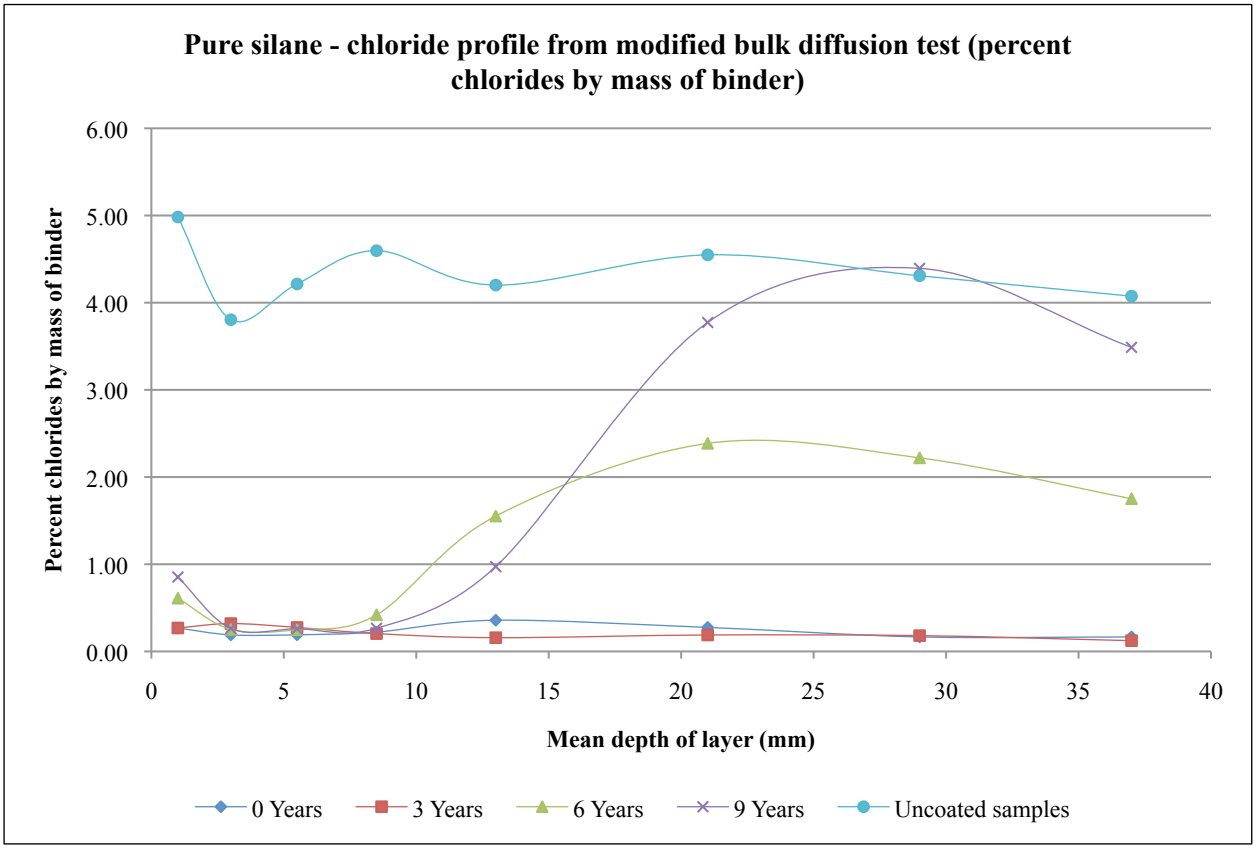

Figure 4.8: Modified bulk diffusion chloride profile - pure silane

Cement based

Other than some white superficial surface staining and chalking the two-part acrylic modified cementitious coating showed no obvious signs of damaged caused by exposure in the UV chamber. Data presented in Figure 5.9 shows that the unweathered cement based coating was effective in reducing the passage of chloride ions. However, samples weathered for 3, 6 and 9 years equivalent show suggest that a certain amount of deterioration has occurred due to the weathering regime. In view of the results presented in Figure 5.9 (pure silane), it is likely that the epoxy sealant was damaged during the weathering process rendering the results questionable. It is therefore not possible to draw definitive conclusions regarding the durability of the cement based coating. The cement based coating has shown to be effective in reducing the ingress of chloride ions however the length of weathering seems to have no clear influence on the protective properties of the coating.

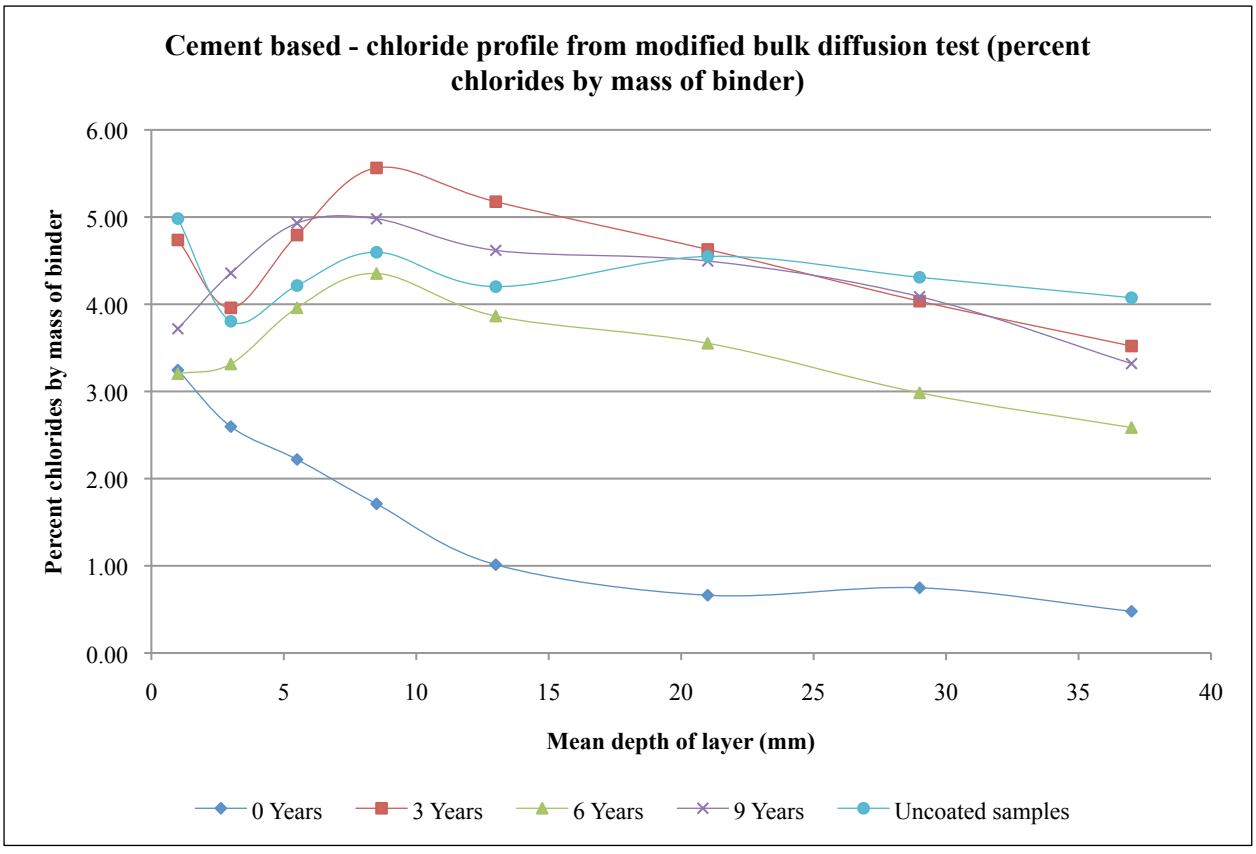

Figure 4.9: Modified bulk diffusion chloride profile - cement based

Cement based FR

Figure 5.10 shows the chloride profile for the cement based FR coating. The test data shows that the coating had little influence in preventing the ingress of chloride ions. Furthermore, the length of weathering had no effect on the performance of the coating.

Initially, better performance was expected from the cement based FR coating due to the inherent elastic properties however, better performance was observed with the cement based coating. Without further information regarding the constituents of the products used in this work it is not possible to determine clear reasons for the differences in performance.

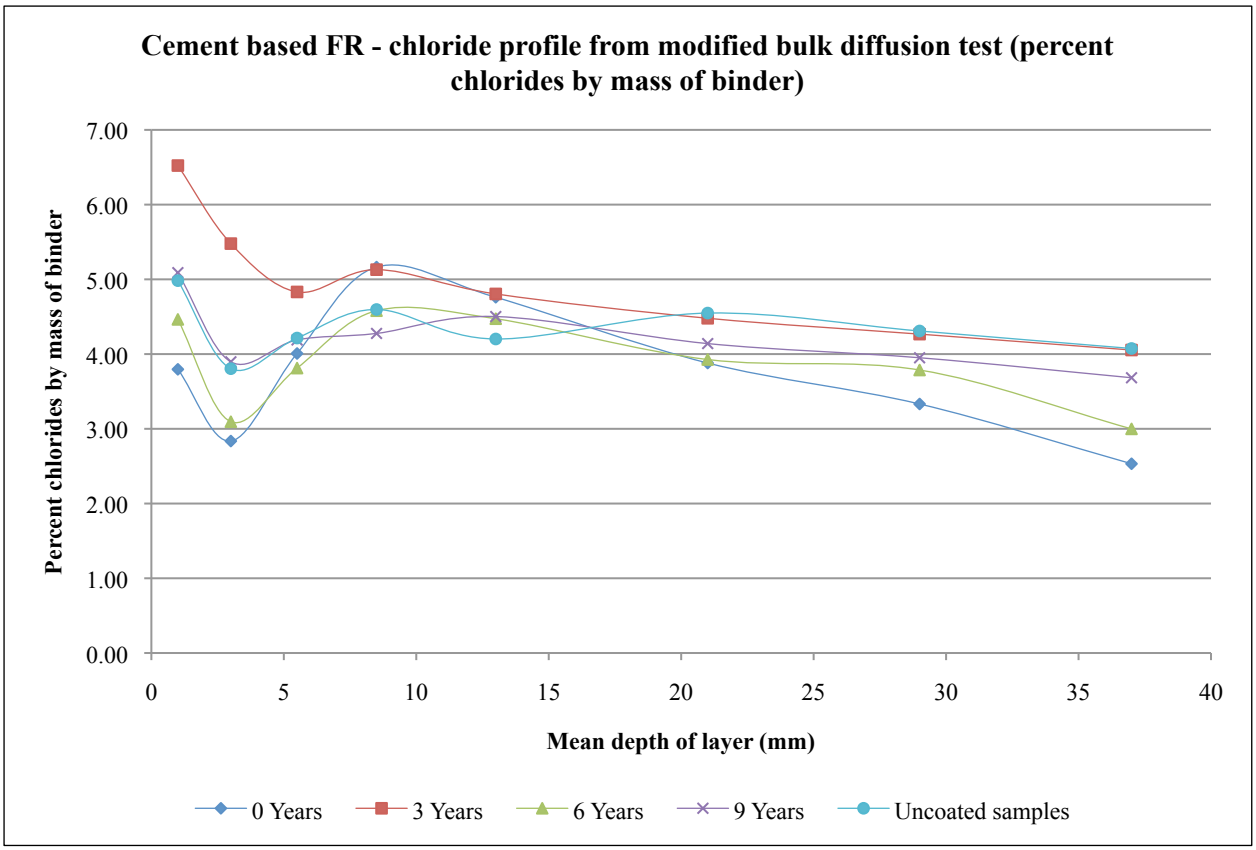

Figure 4.10: Modified bulk diffusion chloride profile - cement based FR

Silane/siloxane

In Figure 5.11, the unweathered silane/siloxane samples show a minor improvement in preventing the passage of chloride ions. The improvement however is not visible in samples weathered for 3, 6 and 9 years equivalent. Test data suggests that the weathering process has reduced the performance of the silane/siloxane samples. However, literature has indicated that silanes and siloxanes are ineffective in preventing moisture ingress under hydrostatic pressure (Thomas, 2002). Therefore, the results are as expected in terms of the literature.

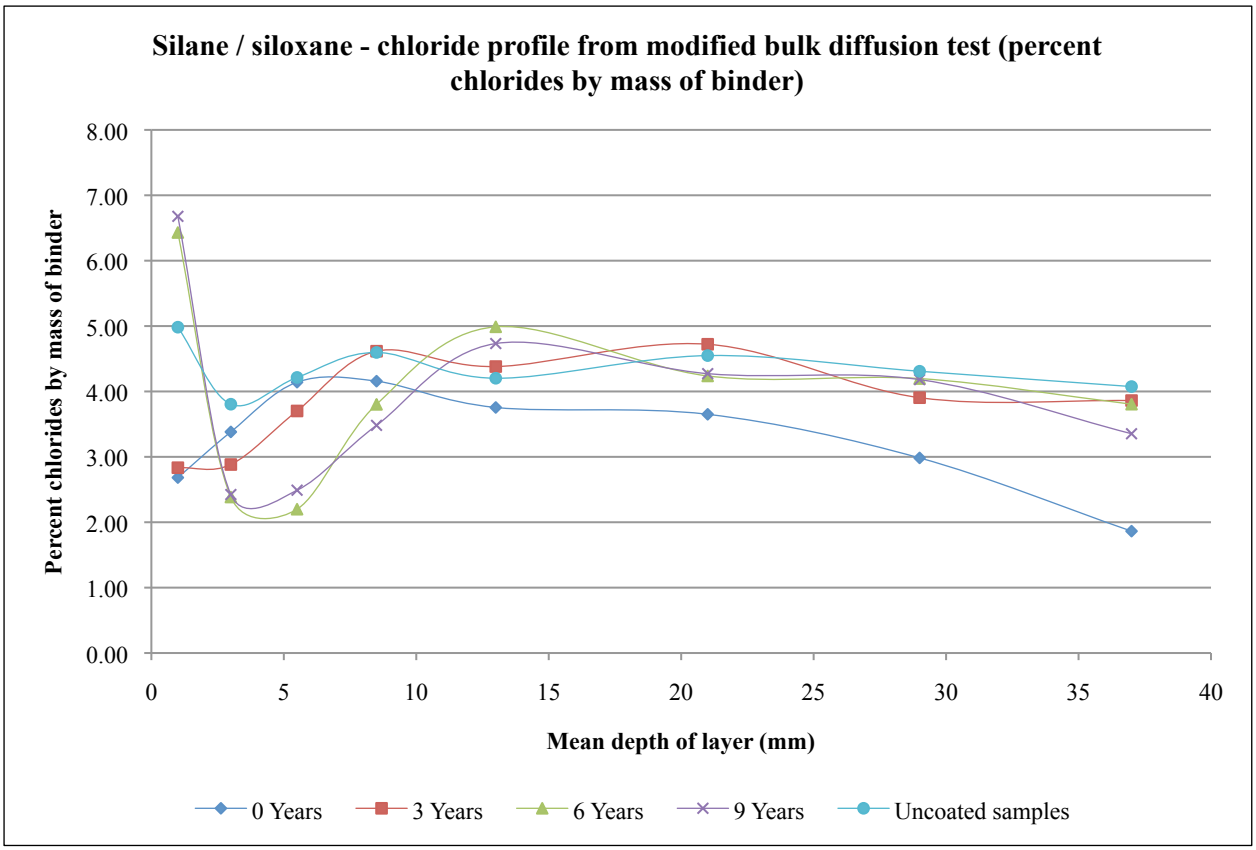

Figure 4.11: Modified bulk diffusion chloride profile - silane/siloxane

4.4 Chloride spray

Uncoated samples

Figure 5.12 shows the results for uncoated samples exposed to splash/spray simulation. The high surface concentration of chlorides can be explained by the formation of salt crystals in the near surface region of the samples during the drying phase of the exposure cycle. The crystals were visible with the naked eye during post exposure inspection of the samples. The results of the splash/spray simulation have been plotted in Figures 5.16 and 5.20 along with the chloride profiles for cement based FR and pure silane surface treatments respectively. Unfortunately, the harsh exposure regime caused damage to the cement based and silane/siloxane surface treatments, thus it was not possible to evaluate the protective properties.

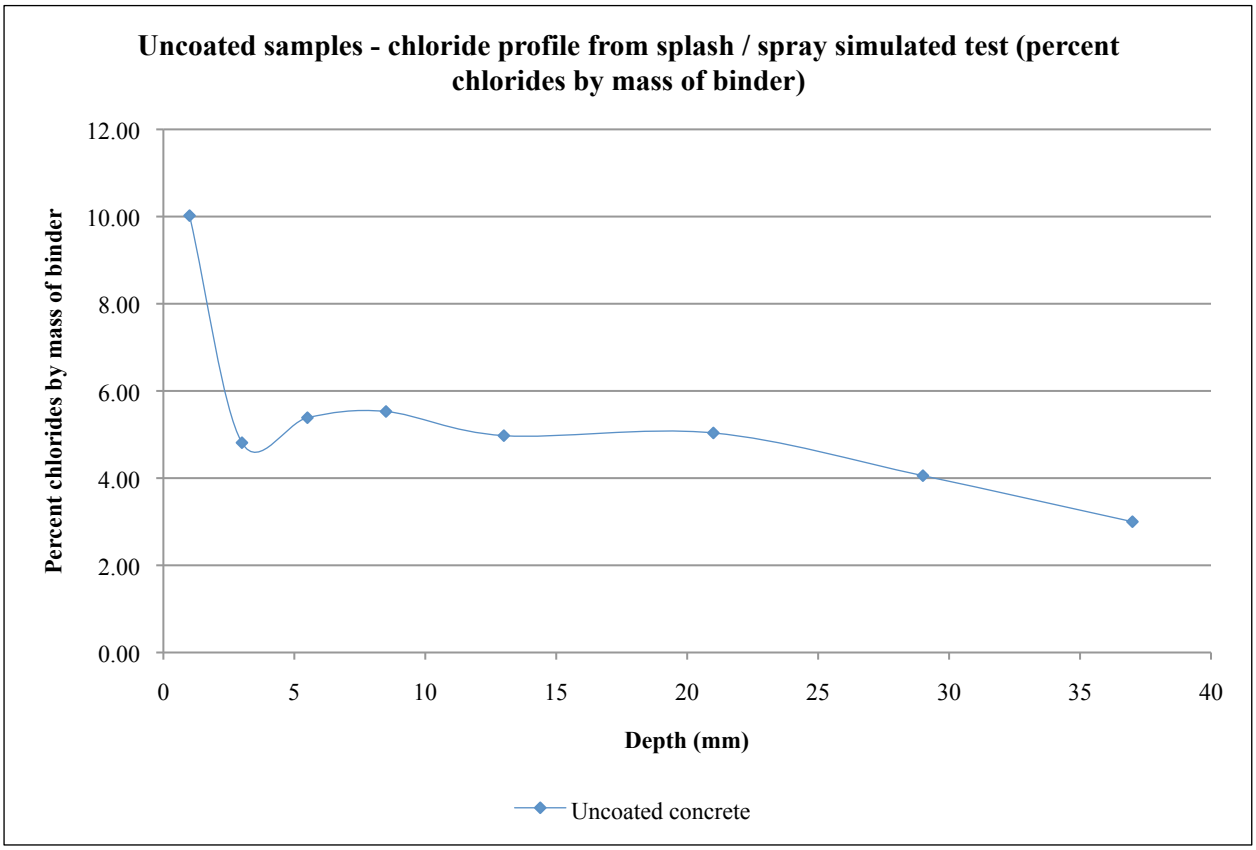

Figure 4.12: Splash/spray simulation chloride profile - uncoated samples

Cement based

With the exception of white staining, the cement based samples showed no visible signs of coating failure (Figure 5.13). The statement may seem invalid in view of the evidence presented in Figures 5.14 and 5.15 but failure was due to cracking at the edges of the samples and eventual delamination of the coating from the substrate. Figure 5.13 shows that the coating appeared to be undamaged but cracking seen in Figure 5.14 let to eventual delamination from the substrate shown in Figure 5.15. Due to the damage caused by the chloride spray chamber, no further testing was performed on the cement based coatings. Since no damage to the coating was detected, it is suspected that the exposure regime was too harsh for the particular surface treatment and as such failure most likely caused by cyclic heating and sudden cooling - a temperature change of approximately 30°C. The test is therefore inconclusive and cannot be used to evaluate the coating performance.

Figure 4.13: Cement based coating after exposure to splash/spray simulation

Figure 4.14: Cracking of the cement based coating after splash/spray simulation

Figure 4.15: Delamination of the cement based coating after splash/spray simulation

Cement based FR

From the test data presented in Figure 5.16, it can be seen that the cement based FR coating had little effect in reducing the passage of chloride ions through the concrete samples. The unweathered and 6 year equivalent weathered samples showed some signs of improvement after approximately 15 mm depth. However, it has already been seen that the epoxy sealant on the 6 and 9 year equivalent weathered samples was most likely damaged due to the exposure conditions. Thus, it possible that the unweathered samples reduced the migration of chlorides through the concrete but unlikely that the 6 year equivalent weathered samples could reduce the passage of chlorides. Therefore, it is not possible to explain the results obtained for the 6 year samples. The 3 and 9 year samples showed results closely resembling the results obtained from the uncoated samples.

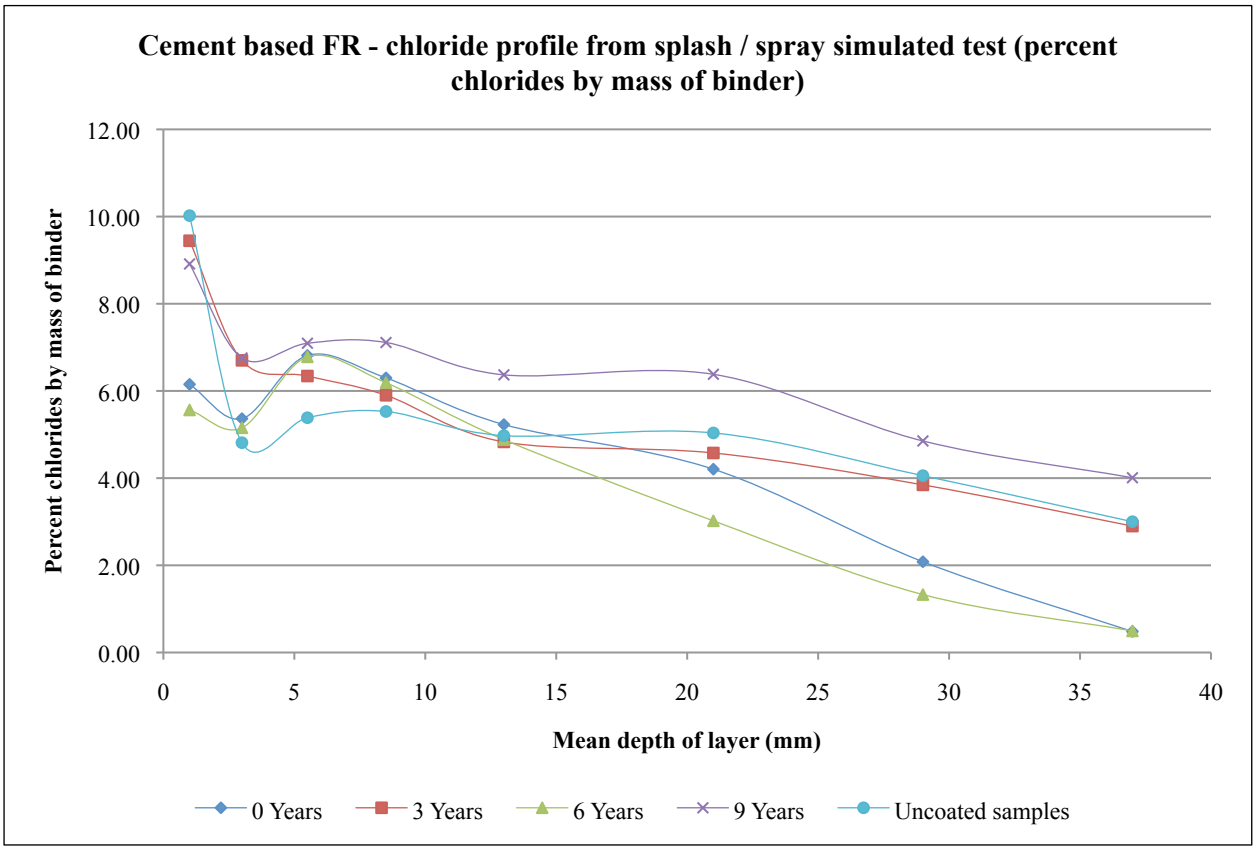

Figure 4.16: Splash/spray simulation chloride profile - cement based FR

Silane/siloxane

During chloride spray, samples treated with the silane/siloxane began to disintegrate after only 14 days. Figures 5.17 and 5.18 show the destruction caused by the chloride spray chamber. Due to the damage caused by the chloride spray exposure regime, samples were not tested for chloride ingress. It is worth noting that the damaged area of the samples was limited to the first 1-2 mm which is seen in Figure 5.22 as the impregnation depth of the silane/siloxane. In Figure 5.19, the damaged surface has been removed to expose the underlying substrate which remained undamaged. Therefore, it would seem that the silane/siloxane treated part of the substrate has been affected by the cyclic heating and sudden cooling exposure of the chloride spray chamber - a temperature change of approximately 30°C. This test was again inconclusive and cannot be used to assess the performance of the coating.

Figure 4.17: Samples treated with silane/siloxane after chloride spray simulation

Figure 4.18: Disintegration of silane/siloxane surface after chloride spray simulation

Figure 4.19: Appearance of silane/siloxane samples after the loose surface had been removed

Pure silane

Results from the chloride spray exposure regime for pure silane samples are shown in Figure 5.20. Theses are the only conclusive results from the chloride spray test and show that the pure silane is effective in reducing the ingress of chlorides. With the exception of the 3 year samples, the results from other weathering ages show a significant performance improvement especially at depths closer to the surface. The unconventional chloride profiles suggest damage to the epoxy sealant occurred during the weathering regime. Thus it is likely that chlorides have entered the sides of the samples and, in a similar manner in the chloride ingress samples, have migrated towards the surface of the sample only to be halted by the silane at a depth of approximately 10 mm. Thus, the pure silane seems to have been successful in reducing the passage of chlorides through the concrete samples.

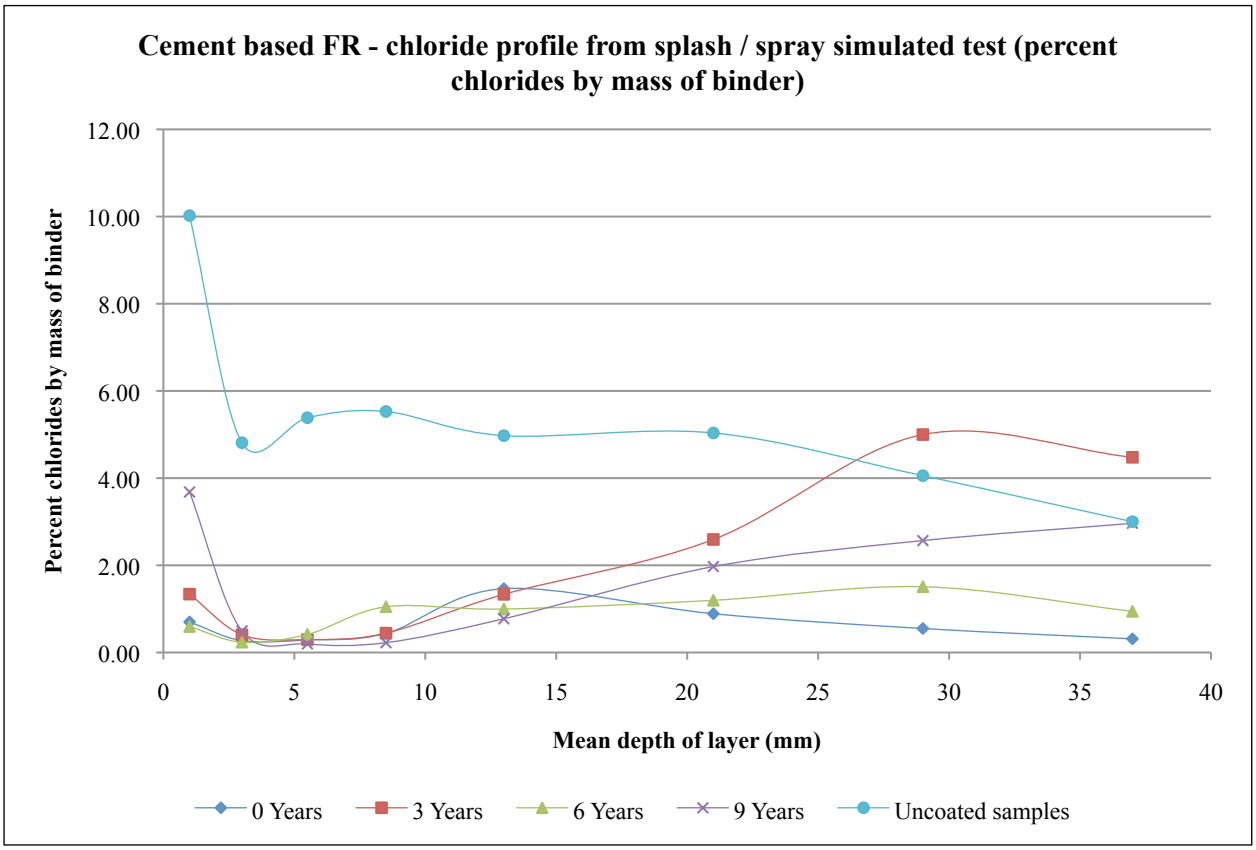

Figure 4.20: Splash/spray simulation chloride profile - pure silane

4.5 Adhesion

Adhesion tests were performed on the coatings to evaluate the bond strength of coatings to the concrete substrate. Due to the low strength concrete used in this project it was not possible to test the acrylic dispersion and acrylic resin to their full potential. It was only possible to obtain a concrete/concrete failure of the acrylic dispersion and acrylic resin samples. In other words, the tensile capacity of the concrete. Thus results from the acrylic dispersion and acrylic resin should be treated with caution as they do not reflect the true bond capacity of the coatings.

The cement based and cement based FR samples exhibited coating/coating failure. In other words, failure between the coating and concrete could not be evaluated, rather, the tensile strength of the coating was measured. Therefore, results for the cement based and cement based FR coatings should be treated with caution since the true bond strength between the concrete and coating has not been measured.

Results have been presented in Figure 5.21, some interesting points can be taken. The acrylic dispersion results show that tensile capacity of the concrete is higher for the 3 year equivalent samples however this is probably due to usual sampling and experimental errors so should not be considered significant. Similarly, the acrylic resin results show the tensile capacity of the concrete increasing with exposure age which could be explained by ongoing hydration with time.

Interestingly, results from the cement based and cement based FR samples both show an increase in tensile capacity of the coating. It is probable that this increase is due to extended hydration caused by elevated heat and exposure to moisture. The results may explain the improved carbonation resistance discussed in 5.2.1. Additionally, the improved coating properties with age confirm the observations made in Figures 5.3 to 5.5 (carbonation results). Full results are presented in Appendix B.

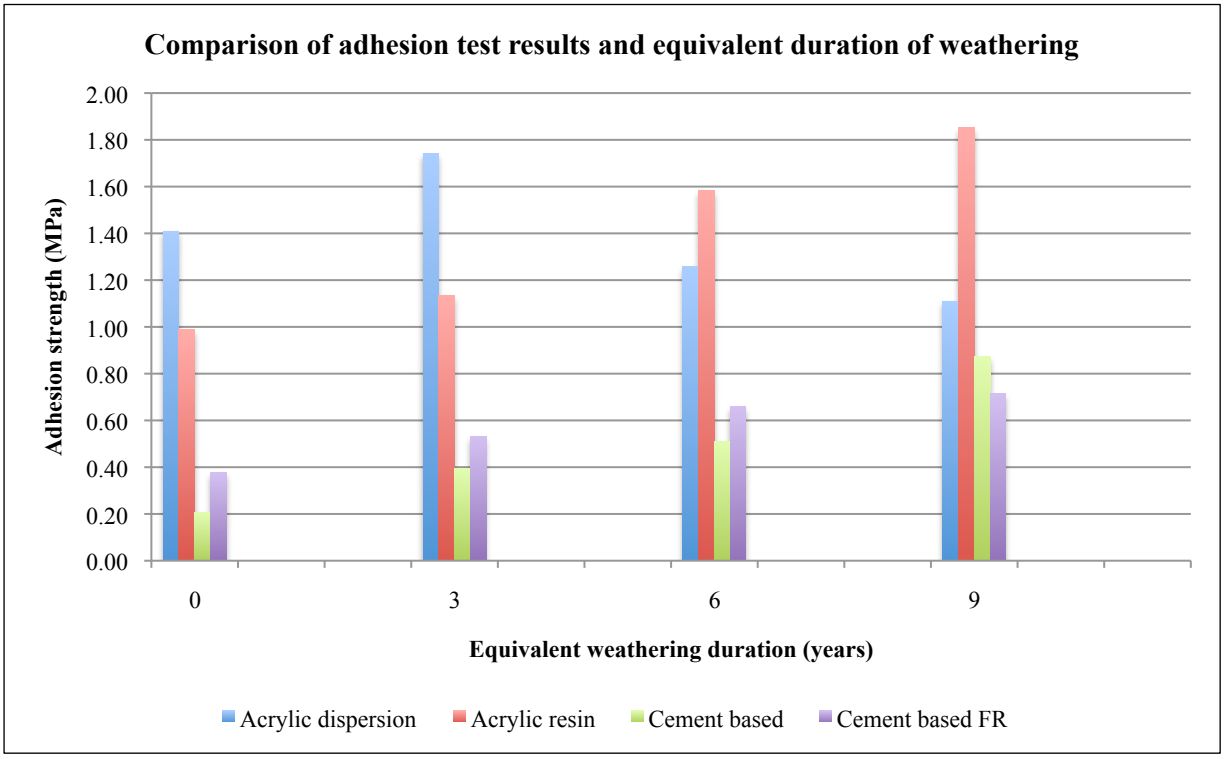

Figure 4.21: Graphical interpretation of adhesion strength and weathering duration

4.6 Impregnation depth of penetrating surface treatments

The impregnation depths of the silane/siloxane and pure silane penetrates were measured by spraying water onto exposed sections of samples. Due to the hydrophobic nature of the surface treatments, water is repelled from the area containing the surface treatment. Figures 5.22 and 5.23 show the impregnation depth of the silane/siloxane and pure silane respectively. The pale area just beneath the surface of the sample represents the impregnation depth of the product. In other words, the concrete in this area was dry to the touch since water was repelled by the hydrophobic surface treatments. The impregnation depths for the silane/siloxane and pure silane were found to be ±1.5 and ±10 mm respectively. The results agree with literature where greater impregnation depths are expected for pure silanes due to the smaller particle sizes (Thomas, 2002). Additionally, results from the chloride ingress and chloride spray tests showed negligible chloride concentrations in the first 10mm of the pure silane samples.

Figure 4.22: Impregnation depth - silane/siloxane

Figure 4.23: Impregnation depth - pure silane

4.7 Summary of results

Poor quality concrete was produced in the laboratory to ensure that it failed to meet minimum carbonation and chloride requirements outline by the South African durability index approach. Due to this, service life estimates for carbonation and chloride ingress were 40 years and less than 1 year at 50 mm depth respectively. In order to improve durability characteristics and hence service life estimates, 6 different surface treatments where applied to concrete specimens. The specimens were then assessed under various weathering and exposure conditions in order to evaluate the effectiveness of reducing the ingress of deleterious agents and durability of the surface treatments.

Acrylic dispersion

The acrylic dispersion showed no signs of damage after exposure in the UV chamber at any of the equivalent weathering periods. According to the carbonation results, the resistance to carbon dioxide of the coating improved with longer periods of UV weathering. With the coating applied to the surface of the samples, the OPI improved from 9.0 to at least 10.0 meaning that a maximum carbonation depth of approximately 20 mm could be expected after 50 years. Therefore, the acrylic dispersion could be used as a measure to prevent carbonation induced corrosion.

Adhesion testing was inconclusive as failure occurred in the concrete and not at the coating/concrete interface. Thus, the adhesion test was only able to measure the tensile capacity of the concrete.

Acrylic resin

No visible signs of damage were observed on the coatings after UV exposure. The acrylic resin showed improved carbonation resistance for longer exposure periods in the UV chamber. The original OPI value of 9.0 was improved to a range of values between 9.4 to 10.3 with increasing weathering periods. With an OPI of 9.4, the carbonation depth at 50 years service life could is expected to be approximately 40 mm.

Failure during adhesion testing occurred in the concrete and not at the concrete/coating interface. The results therefore show the tensile capacity of the concrete. Improved results with weathering duration indicate that improved hydration was likely to have occurred as a result of the increased temperature in the weathering chamber. The results however should be viewed with some caution as the same trend was not observed with the acrylic dispersion samples which underwent the same weathering regime but showed significantly different results.

Cement based

Other than some white superficial surface staining and chalking the cementitious coating showed no obvious signs of damaged caused by exposure in the UV chamber. Improved carbonation results for older samples seem to suggest that the coating is relatively unaffected by exposure to UV weathering. The coating improved the OPI value from 9.0 to values ranging from 9.4 to 10.3. The carbonation depth after 50 years can be expected to be approximately 40 mm with an OPI of 9.4.

The tensile strength of the coating improved with longer exposure times since failure occurred in the coating. Improved tensile capacity of the coating can be accredited to improved hydration due to the warm, moist environment of the weathering chamber.

Unweathered samples have shown improved signs of chloride ingress. However, samples weathered for 3, 6 and 9 equivalent years do not show the same pattern and the results are similar to those obtained for the uncoated samples. In view of other samples undergoing the same weathering regime, the most likely explanation of these results is due to failure of the epoxy sealant.

Complete delamination of the cement based coating of all equivalent weathering ages occurred in the salt spray chamber rendering the test inconclusive.

Cement based FR

Apart from some chalking on the surface of the fibre reinforced cementitious coating on removal from the UV chamber, no signs of damage were visible. Adhesion results showed a minor improvement for increasing weathering ages of the cement based FR coating. The improved tensile capacity of the coating is accredited to extended hydration caused by the warm, moist conditions inside the weathering chamber.

The carbonation resistance was found to improve with extended weathering durations. Subsequent to coating application, the OPI value increased from 9.0 to at least 10.2 translating to a carbonation depth of approximately 10 mm after 50 years service life.

The coating had little effect on the chloride resistance of the concrete. The chloride profiles obtained for the weathered and unweathered samples is similar to the profile obtained for the uncoated samples. This trend continued into the salt spray results where no significant differences between the coated and uncoated chloride profiles were observed. Even though the epoxy sealant was most likely damaged during the weathering process, the results obtained from the unweathered samples show that the cement based FR coating is ineffective in reducing chloride ingress.

Silane/siloxane

Due to the impregnating nature of the surface treatment, no signs of deterioration caused by the UV chamber could be observed. The chloride ingress test results showed no differences between the coated and uncoated samples. This was an expected result as silane/siloxanes are not recommended for use under hydrostatic pressure. The test was carried out to investigate whether the surface treatment could provide any resistance to the penetration of chloride ions under hydrostatic pressure (Thomas, 2002).

Unfortunately, results could not be obtained from the chloride spray test as the surface of the concrete completely disintegrated after approximately 2 weeks in the chamber. Crumbling of the surface occurred in the impregnation zone of the coating rendering the test inconclusive.

Pure silane

Like silane/siloxanes, pure silane coatings impregnate the concrete surface, thus no signs of damage could be observed on the surface of the samples. Under low hydrostatic pressure, results from the chloride ingress test suggest that pure silane treatments could be used to prevent the ingress of chloride ions. These results however are contradictory to the literature which suggests that pure silanes are not effective at preventing chloride ingress. (Keer, 1992).

In both the chloride ingress salt spray tests, the pure silane treatment was effective in reducing chloride ingress. Therefore, pure silane coatings can effectively be used to prevent the ingress of chloride ions even under harsh weathering conditions.

5 Conclusions and recommendations

In recent years, durability design of reinforced concrete structures has increasingly gained importance, owing to large governmental spending on the repair of existing concrete structures (Emmons and Vaysburd, 1996). In many countries, the budget for repairing existing infrastructure already exceeds that of building new infrastructure. A preliminary investigation has suggested that the use of coatings to restrict the passage of deleterious agents is an acceptable method of corrosion prevention. A clear understanding of the corrosion process and the method of protection however is still required if coatings are to be used as a method of corrosion prevention.

5.1 Surface treatments

Poor quality concrete failing to meet minimum requirements specified by the South African durability index approach was produced in the laboratory. A total of six surface treatments were applied to concrete samples in order to prevent the ingress of carbon dioxide and chloride ions. The samples were then exposed to different weathering and exposure regimes in order to evaluate the performance and longevity of the surface treatments.

Acrylic dispersion

Performance of the coating was seen to improve with increased weathering periods. The OPI was seen to improve from 9.0 to values ranging from 10.0 to 10.4 meaning that a maximum carbonation depth of approximately 20 mm could be expected after 50 years. Therefore, the acrylic dispersion was effective in improving the carbonation resistance for all equivalent weathering regimes and can be used to prevent carbonation induced corrosion.

Acrylic resin

Carbonation resistance was seen to improve for longer exposure periods in the UV chamber. The original OPI value of 9.0 was improved to a range of values between 9.4 to 10.3 meaning that the maximum carbonation depth after 50 years service life is expected to be approximately 40 mm. Therefore, the acrylic resin was effective in reducing the passage of carbon dioxide for all equivalent weathering regimes. Corrosion caused by carbonation can effectively be prevented with the acrylic resin coating. Like the acrylic dispersion, ease of application makes the acrylic resin a more attractive option than the cement based and cement based FR coatings for corrosion prevention especially since it was shown to be unaffected by weathering.

Cement based

Other than some white superficial surface staining and chalking the cementitious coating showed no obvious signs of damaged caused by exposure in the UV chamber. Carbonation resistance was seen to improve for samples exposed to longer periods of weathering and the initial OPI value of 9.0 was improved to a range of values between 9.4 and 10.3 meaning that the maximum carbonation depth after 50 years is expected to be 40 mm. Thus, the cement based coating is able to effectively improve carbonation resistance and can be considered as an option to prevent corrosion in structures failing to meet minimum OPI requirements.

Coating application is relatively more labour intensive than the acrylic dispersion and resin making it a less desirable option for corrosion prevention.

In the chloride ingress test, unweathered samples reduced chloride ingress however, samples weathered for 3, 6 and 9 equivalent years do not show the same pattern and the results are similar to those obtained for the uncoated samples. In view of the previously discussed epoxy sealant failure, test results are inconclusive and should not be used to evaluate the performance or longevity of the coating.

Complete delamination of the cement based coating at all equivalent weathering ages occurred in the salt spray chamber rendering the test inconclusive.

Cement based FR

The carbonation resistance was found to improve with extended weathering durations. Subsequent to coating application, the OPI value increased from 9.0 to a range of values between 10.2 and 10.4 translating to a carbonation depth of approximately 10 mm after 50 years service life. Therefore, the cement based FR coating was able to effectively reduce the passage of carbon dioxide. The coating showed excellent carbonation resistance however due to the difficult application process the acrylic dispersion and acrylic resin are preferable options.

The chloride ingress test chloride profiles obtained for the weathered and unweathered samples is similar to the profile obtained for the uncoated samples. The results for the weathered samples were expected based on the epoxy sealant failure however the unweathered samples had little effect in reducing the passage of chloride ions thus it must be concluded that the cement based FR coating ineffective at reducing the passage of chloride ions.

Salt spray test results showed no significant differences between the uncoated and coated sample chloride profiles. Even though the epoxy sealant was most likely damaged during the weathering process, results obtained from the unweathered samples show that the cement based FR coating is ineffective in reducing chloride ingress. Therefore, the cement based FR coating should not be considered as an option to reduce the passage of chloride ions.

Silane/siloxane

Due to the impregnating nature of the surface treatment, no signs of deterioration caused by the UV chamber could be observed. The chloride ingress test results showed no differences between the coated and uncoated samples for all weathering ages. Therefore, as expected from literature (and product literature), silane/siloxanes should not be used to prevent chloride ingress under hydrostatic pressure or where pooling on a horizontal surface may occur (Thomas, 2002).

Crumbling of the surface occurred in the impregnation zone of the silane/siloxane during salt spray exposure rendering the test inconclusive as no results could be obtained. Therefore, the salt spray exposure conditions were most likely too harsh for the silane/siloxane.

Pure silane

In both the chloride ingress and salt spray tests, the pure silane treatment was effective in reducing chloride ingress for all weathering ages. Due to their hydrophobic protective properties (and according to product literature) pure silane coatings can effectively be used to prevent the ingress of chloride ions even under harsh exposure conditions. The results are agreeable to observations made in literature however the effectiveness of the coating to prevent moisture ingress under hydrostatic pressure should be investigated further as literature has suggested that silanes are ineffective under such conditions (Kay, 1992; Keer, 1992). In addition to the protective properties, pure silane type coatings are easily applied to structures and are largely unaffected by weathering making them a preferred option for the marine environment (Kay, 1992).

5.2 Weathering and exposure regimes

During the chloride ingress and salt spray testing, it became evident that the epoxy used to seal the sides of the samples became damaged. This allowed deleterious substances to enter the concrete sample through the sides rendering a number of samples and tests inconclusive. Unweathered samples however behaved as expected. It was expected that the sealant chosen in this work would be unaffected by the weathering regime but unfortunately it was the reason for inconclusive results. Therefore, any future work should include an investigation into the protective properties and durability of all materials used.

5.3 Recommendations

The potential for using surface treatments to prevent the ingress of corrosion causing agents (carbon dioxide, chloride ions and moisture) is presented in literature but the extent of protection and durability of these products is largely unknown. This laboratory investigation was developed to evaluate the performance and longevity of surface treatments under accelerated weathering and exposure conditions.

It was found that a number of coatings could be used to increase the carbonation resistance of poor quality concrete however, less was discovered about the protective properties of the coatings used to improve chloride ion resistance. Due to shortfalls in the testing regime of this project, further work will be required to draw more conclusions from tests which were inconclusive. The scope of work however should be limited to testing indicators directly linked to the South African durability approach to optimise the limited number of samples available for testing.

Regardless of remedial measures available to engineers, good quality concrete must always be a top priority to ensure the service life of reinforced concrete structures. This work has shown that certain products can be used successfully to prevent corrosion caused by the ingress of carbon dioxide and chloride ions but it has also highlighted the current lack of knowledge and standardised performance indicators of coating performance. It is for this reason that engineers should pay close attention to manufacturer’s guidelines when using surface treatments to improve durability.

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Appendix A - Product information sheets

A1 Acrylic dispersion

Construction

Product Data Sheet
Edition 01/12/2005
Identification no:
02 03 03 02 05
Sikagard®-550 W Elastic ZA

Sikagard®-550 W Elastic ZA

Crack bridging protective coating for concrete

Product Description

Sikagard®-550 W Elastic ZA is a one part, plasto-elastic coating based on UV-curing acrylic dispersion with excellent crack-bridging properties even at temperatures below 0°C.

Uses

- Protection and enhancement of concrete structures (normal and lightweight concrete), especially exposed concrete surfaces with a risk of cracking
- With concrete repair works as an elastic protective top coating on Sika® mortar thin layer levelling mortar (refer to product data sheet)

Characteristics / Advantages

- Crack-bridging even at low temperatures (-20°C)
- High diffusion resistance against CO_2 reducing the rate of carbonation
- Water vapour permeable
- Very good resistance against weathering and ageing
- Can be diluted with water
- Environmentally friendly (solvent free)
- Reduced tendency to dirt pick up and contamination

Tests

Approval / Standards

Test according to ZTV SIBOS-D II from the Polymer Institute dd 16.10.01 Nr. P2438

Test according to ZTV SIBOS-D II from the Polymer Institute dd 16.10.01 Nr. P2436

The product is included in a compilation of tested products and systems as per OS 5a (OS DII) at the German Institute of Road Systems and is registered in the LCPC (French Laboratoire des Ponts et Chaussées) list of approved paint systems for civil engineering structures.

Product Data

Form

Appearance / Colours: Thixotropic liquid available in almost every colour shade.

Packaging: 5, 20 and 200 litre containers

Storage

Storage Conditions / Shelf-Life: 12 months from date of production if stored properly (+5°C and +30°C) in undamaged and unopened original sealed packaging in cool and dry conditions. Protect from direct sunlight and frost.

Technical Data

Chemical Base	Acrylate dispersion
Density	~ 1.40 kg/l (at +25°C)
Solid Volume	~ 53.4%
Layer Thickness	d_{minp} (minimum required thickness to achieve the required characteristics - CO_2 equivalent air thickness of 50m and crack bridging) = 200 microns. D_{maxp} (maximum required thickness not to go beyond the H_2O equivalent air thickness of 4m) = 1635 microns.

Carbon Dioxyde Diffusion Coefficient (μCO_2)

Dry film thickness	d = 337µm
Equivalent air layer thickness	$S_{D,}$ CO_2 = 84m
Diffusion coefficient CO_2	$\mu CO_2 = 2.5 \times 10^5$
Requirements for protection	≥ 50m

Water Vapour Diffusion Coefficient (μH_2O)

Dry film thickness	d = 319µm
Equivalent air layer thickness	$S_{D,}$ H_2O = 0.78 m
Diffusion coefficient H_2O	$\mu H_2O = 2.5 \times 10^3$
Requirements for breathability	≤ 4m

Mechanical / Physical Properties

Elongation at Tear	Elongation at break at room temperature (not exposed to weathering): 63% Elongation at break at -20°C: 32%
Crack-Bridging Capacity	Class I_T according to ZTV SIB 90-TL/TP OS

System Information

System Structure

System	Product [1]	Number of applications
Priming	Sikagard®-550 W Primer	1
Top coat	Sikagard®-550 W Elastic ZA	2

Note[1]
Please refer to the respective data sheet for additional information.

Note[3]
The number of layer depends on the pore structure in order to achieve a pore-free surface.

Application Details

Consumption

Product	Per coat
Sikagard®-550W Primer	~ 6.0m²/litre
Sikagard®-550 W Elastic ZA	~ 4.0 – 6.0m²/litre

Substrate Preparation

Exposed concrete without existing coating:

The surface must be dry, sound and free from loose and friable particles. Suitable preparation methods are steam cleaning, high pressure water jetting or blastcleaning.

New concrete must be at least 28 days old.

If required, a levelling pore sealer (e.g. Sika® MonoTop®-620) should be applied. For cement based products, allow a curing time of at least 4 days before coating.

Exposed concrete with existing coating:

Existing coatings must be tested to confirm their adhesion to the substrate - adhesion test average >0,8 N/mm² with no single value below 0.5 N/mm².

Inadequate adhesion:
Existing coatings must be completely removed by suitable methods and the substrate must be sufficiently sound and suitable to be coated as above.

Adequate adhesion:
Thorough cleaning of all surfaces by steam cleaning or high pressure water jetting

In case of doubt, carry out adherence testing to determine which primer is most suitable - wait at least 2 weeks prior to conduct the adhesion test - an average value of 0.8 N/mm² is required with no single value below 0.5 N/mm².

Application Conditions / Limitations

Substrate Temperature	+8°C min. / +30°C max.
Ambient Temperature	+8°C min. / +30°C max.
Relative Air Humidity	< 80%
Dew Point	Temperature must be at least 3°C above dew point.

Application Instructions

Mixing

The materials are supplied ready for use. Stir thoroughly prior to application.

Application Method / Tools

Apply Sikagard®-550W Elastic Primer evenly onto the substrate. For use on very

Sikagard®-550 W Elastic ZA can be applied by brush, roller or airless spray.

Cleaning of Tools

Clean all tools and application equipment with clean water immediately after use. Hardened / cured material can only be removed mechanically.

For Sikagard®-550W Elastic Primer use Sika® Kwiklean.

Waiting Time / Overcoatability

Waiting time between coats at +20°C substrate temperature:

Previous coating	Waiting time	Next coating
Sikagard®-550 W Elastic Primer	8 hours min.	Sikagard®-550 W Elastic ZA
Sikagard®-550 W Elastic ZA	8 hours min.	Sikagard®-550 W Elastic ZA

Note: When application is on existing coatings, the waiting time for the primer will increase by 100%.

Refresher coats of Sikagard®-550 W Elastic ZA can be applied without priming if the existing coat has been thoroughly cleaned.

Notes on Application / Limitations

Do not apply when there is:

- Expected rain
- Relative humidity >80%
- Temperature below +8°C and/or below dew point
- Concrete younger than 28 days

The system is resistant to aggressive atmospheric influences.

Curing Details

Curing Treatment

Sikagard®-550 W Elastic ZA does not require any special curing but must be protected from rain for at least 4 hours at +20°C.

Applied Product ready for use

Full cure: ~ 7 days at +20°C

Notes

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

Local Restrictions

Please note that as a result of specific local regulations the performance of this product may vary from country to country. Please consult the local Product Data Sheet for the exact description of the product uses.

Construction

Health and Safety Information

Protective Measures	Sikagard®-550 W Elastic Primer contains volatile, flammable liquids, observe relevant regulations concerning health and safety at work. Keep away from ignition sources, refrain from smoking. Use only in well ventilated spaces. Risk of serious damage to eyes. Wear protective goggles and gloves made of appropriate plastic material. No special precautionary measures are necessary for Sikagard®-550 W Elastic ZA. General protective and hygiene measures shall be taken. For more detailed information, please ask for the Material Safety Data Sheet.
Ecology	
Transportation Class	
Important Notes	Residues of material must be removed according to local regulations. Fully cured material can be disposed of as household waste under agreement with the responsible local authorities. Detailed health and safety information as well as detailed precautionary measures e.g. physical, toxicological and ecological data can be obtained from the Material Safety Data Sheet.
Toxicity	

Legal Notes

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request or access on the Internet under www.sika.co.za.

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A2 Acrylic resin

Construction

Product Data Sheet
Edition 18/09/2006
Identification no:
02 03 03 03 006 0 000010
SikaColor®-671 W

SikaColor®-671 W

Protective and decorative coating for facades with a smooth and coloured finish

Product Description

SikaColor®-671 W is a one part coating based on water dispersed acrylic resin designed for protection, decoration and waterproofing of facades, with a smooth coloured finish.

Uses

- As a protective decorative and waterproofing coating for concrete, mortar, brick and stone facades
- As an interior walls decorative coating in public buildings such as hospitals, schools and museums etc.
- As a base coat for the subsequent application of the textured top coat - SikaColor®-672 W

Characteristics / Advantages

- High diffusion resistance against CO_2, reducing the rate of carbonation
- Water vapour permeable, allowing the substrate to breathe
- Excellent resistance against weathering and ageing
- Waterproof against driven rain
- Environmentally friendly, solvent free product
- Easy application
- High alkali resistance
- Non tacky with reduced tendency to dirt-pick up
- Good opacity and covering ability

Product Data

Form

Appearance / Colours	Cream and selected colours according to the colour chart.
Packaging	25 kg tins

Storage

Storage Conditions / Shelf-Life	12 months from date of production if stored properly in unopened and undamaged original sealed packaging in cool and dry conditions. Protect from direct sunlight and frost.

Technical Data

Chemical Base	Filled acrylate resin dispersion.
Density	~ 1.40 kg/l (at +20°C)
Solid Volume	~ 68% by volume
Solid Content	~ 55% by weight
Layer Thickness	60 microns min. (per layer) / 120 microns max. (per layer)

Carbon Dioxyde Diffusion Coefficient (μCO_2)

Dry film thickness	d = 120 µm
Equivalent air layer thickness	$S_{D,}\ CO_2$ = 384 m
Diffusion coefficient CO_2	$\mu CO_2 = 3.2 \times 10^6$
Protection requirements	≥ 50 m

Water Vapour Diffusion Coefficient (μH_2O)

Dry film thickness	d = 120 µm
Equivalent air layer thickness	$S_{D,}\ H_2O$ = 0.13 m
Diffusion coefficient H_2O	μH_2O = 1119
Breathability requirements	≤ 4 m

System Information

System Structure

Normal conditions:

System	Product	Number of applications
Priming	Not required	
Top coat	SikaColor®-671 W	2

Very absorbent substrates:

Priming	SikaColor®-671 W diluted with 10% water	1
Top coat	SikaColor®-671 W	1 - 2

Very dense substrates:

Priming	Sikagard®-551 S Elastic Primer	1
Top coat	SikaColor®-671 W	2

Marine environment or concrete exposed to de-icing salts:

Priming	Sikagard® hydrophobic impregnation (refer to local Product Data Sheets)	1
Top coat	SikaColor®-671 W	2

Note: A third coat of SikaColor®-671 W may be required with light or bright colour shades in order to achieve good opacity (hiding power).

Application Details

Consumption

~ 200 g/m^2 per coat which is equivalent to a dry film thickness of ~ 60 microns (assuming a loss of 20%).

Substrate Preparation

Exposed concrete without old coatings:
The surface must be clean, sound, dry and free from loose or friable particles. Suitable preparation methods are steam, high pressure water jetting or blastcleaning. Cementitious Sika® thin renderings must be cured at least 5 days before coating.

Exposed concrete with old coating:
Old coatings must be tested for their adequate adhesion to the substrate - adhesion test average > 0.8 N/mm^2 with no single value below 0.5 N/mm^2.

- If there is inadequate adhesion then:
  Old coatings must be completely removed by suitable methods and the substrate must be sufficiently sound and prepared before coating.
- If there is adequate adhesion then:
  Thorough cleaning of all surfaces is required, by steam cleaning or high pressure water jetting.

Application Conditions / Limitations

Substrate Temperature

+8°C min. / +35°C max.

Ambient Temperature

+8°C min. / +35°C max.

Relative Air Humidity

< 80%

Dew Point

Application temperature must be at least 3°C above dew point.

Application Instructions

Mixing

For normal usage, SikaColor®-671 W is supplied ready for use.
Stir thoroughly prior to application.

For use on very absorbent substrates, add up to a maximum of 10% water - stir well prior to use.

Application Method / Tools

SikaColor®-671 W can be applied by brush, short pile roller or airless spray.

The second coat should be applied in a cross wise direction to achieve optimum opacity.

Cleaning of Tools

Clean all tools and application equipment with water immediately after use.
Hardened / cured material can only be removed mechanically.

Waiting Time / Overcoatability

Waiting time between coats:

Previous coating	Waiting time			Next coating
	8 - 10°C	15 - 23°C	30 - 35°C	
Sikagard®-551 S Elastic Primer	24 hours	12 hours	6 hours	SikaColor® -671 W
Sikagard® hydrophobic impregnation	Refer to local Product Data Sheet			Sikagard® -671 W ElastoColor
SikaColor® -671 W	24 hours	6 hours	6 hours	SikaColor® -671 W

Note: A refresher coat of SikaColor® 671 W can be applied without priming if the existing coating has been thoroughly cleaned.

Construction

Notes on Application / Limitations	Do not apply when: - Rain or frost is expected. - Relative humidity is above 80%. - The temperature is below +8°C and/or below dew point conditions. - On wet surfaces. At temperatures below +8°C on very absorbent substrates with strong winds, there is a risk of drying cracks and reduced adhesion so these conditions should be avoided. SikaColor®-671 W is resistant to common atmospheric pollutants and highly resistant to alkalinity from cement based substrate.

Curing Details

Curing Treatment	SikaColor®-671 W does not require any special curing but must be protected from rain for at least 1 hour at +23°C.
Applied Product ready for use	Final drying: ~ 4 hours at +23°C.
Value Base	All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.
Local Restrictions	Please note that as a result of specific local regulations the performance of this product may vary from country to country. Please consult the local Product Data Sheet for the exact description of the application fields.
Health and Safety Information	For information and advice on the safe handling, storage and disposal of chemical products, users should refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.
Legal Notes	The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

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ISO 14001 ISO 9001

A3 Cement based

Construction

Product Data Sheet
Edition 11/12/2005
Identification no:
02 07 01 01 05
SikaTop® Seal-107 ZA

SikaTop® Seal-107 ZA

Waterproofing damp-proofing cementitious slurry

Product Description

SikaTop® Seal-107 ZA is a two part polymer modified cementitious waterproof mortar slurry comprising of a liquid polymer and a cement-based mix incorporating special admixtures.

Uses

SikaTop® Seal-107 ZA is used for:

- Interior and exterior waterproofing and damp-proofing of concrete, cementitious rendering, brickwork and blockwork
- Protection of concrete structures against the effects of de-icing salts and freeze-thaw attack
- Rigid waterproofing of basement walls in new construction and refurbishment
- Pore/blowhole filling
- Waterproofing basement and cellars (not subject to hydrostatic water pressure)
- Sealing fine “hairline” cracks in concrete structures (not subject to movement)
- Levelling mortar for concrete repair works

Characteristics / Advantages

- Easy to apply by brush or in thin trowel applications
- No water required
- Prebatched components
- Hand or spray applied
- Easy and fast mixing
- Very good adhesion
- Protects concrete against carbonation
- Protects against water penetration
- Non-corrosive to steel or iron
- Overpaintable
- Approved for potable water contact

Tests

Approval / Standards

Product Data

Form

Appearance /Colours	Part A:	white liquid
	Part B:	grey or white powder
	Mixed product:	cement grey or off-white
Packaging	25kg units (20 kg bag and 5 kg pail)	

Storage

Storage Conditions / Shelf-Life	6 months from date of production if stored properly in undamaged and unopened original sealed packaging in dry and cool conditions. Liquid component must be protected from frost.

Technical Data

Chemical Base	Part A: liquid polymer and additive Part B: portland cement selected aggregate and admixtures
Density	Fresh mortar density: ~ 2.00 kg/l
Layer Thickness	Min. 0.75mm min – max. 1.5mm

Mechanical / Physical Properties

Compressive Strength (According to EN 196-1)

3 days	~ 7 N/mm^2
28 days	~ 20 N/mm^2

Bond Strength 2.0 to 3.0 N/mm^2 (failure in substrate)

System Information

Application Details

Consumption / Dosage	Dependent on the substrate roughness, surface profile and thickness of the layer applied. As a guide, ~ 2.0 kg/m^2/mm (excluding allowances for loss wastage, surface profile and porosity, etc.). 1 unit of 25kg yields ~ 12.5 litres of mortar.
Substrate Quality	The substrate must be structurally sound and free of all traces of contaminants, loose and friable particles, cement laitance, oils and grease etc. The concrete “pull off” (tensile adhesive) strength must be > 1.0 N/mm^2.
Substrate Preparation	*General:* The substrate must be prepared by suitable mechanical preparation techniques such as high pressure water jetting, needle guns, blastcleaning, scabblers etc. and properly pre-wetted to a saturated surface dry condition. *For pore/blowhole filling:* Blastclean to remove all contaminants including from within the pores/blowholes. *As a levelling mortar:* Prepare and clean all surfaces by suitable mechanical means such as abrasive blast cleaning or equivalent to ensure cement laitance, surface contamination and all existing coatings are removed and all blowholes and honeycombed areas are exposed. The resultant surface must be profiled to achieve maximum bond strength.

Application Conditions / Limitations

Substrate Temperature	+8°C min. / +35°C max.
Ambient Temperature	+8°C min. / +35°C max.

Application Instructions

Mixing	Used as slurry: A : B = 1 : 4 (parts by weight) Used as mortar: A : B 1 : 4.5 (parts by weight)
Mixing Time	~ 3 minutes
Mixing Tools	SikaTop® Seal-107 ZA must be mechanically mixed using a forced action mixer or in a clean drum using a drill and paddle (max. 500 rpm). A normal concrete free fall mixer is NOT suitable.
Application Method / Tools	Shake part A before using it. Pour approximately half of part A into the mixing container and add part B slowly while mixing. Add the remainder of part A and continue mixing until a uniform lump free consistency is achieved. The surface must be pre-wetted to a saturated surface dry condition before application. *As a slurry:* Apply the mixed SikaTop® Seal 107 either mechanically, by spray or by hand using a stiff brush. Applied in the same direction. Apply the 2nd coat of SikaTop® Seal-107 ZA, applied by brush in crosswise direction to the first application as soon as first coat has hardened. *As a mortar:* When SikaTop® Seal-107 ZA is applied by trowel (e.g. for a smooth surface finish), the product must be mixed with a 10% reduction of part A (~ 1A : 4.5B). Apply the 2nd coat of SikaTop® Seal-107 ZA as soon as the first coat has hardened. For pore/blowhole filling, tightly trowel into the pores/blowholes of the surface.
Cleaning of Tools	Clean all tools and application equipment with clean water immediately after use. Hardened / cured material can only be removed mechanically.
Potlife	~ 30 minutes at +20°C
Waiting Time / Overcoatability	*Waiting time between coats* +10°C: ~ 12 hours +20°C: ~ 6 hours +30°C: ~ 3 hours If waiting time period exceeds 24 hours, lightly blastclean the surface. SikaTop® Seal-107 ZA can be overpainted using solvent based primers or coatings. SikaTop® Seal-107 ZA must cure for a minimum of 7 days before overcoating.
Notes on Application / Limitations	SikaTop® Seal-107 ZA is not a decorative treatment and may display signs of "blooming" after rain or in damp weather. This does not affect the performance of the coating, in any way. Where SikaTop® Seal-107 ZA will be visible after completion of the works, then the off-white colour, which is aesthetically more pleasing, should be used. Avoid application in direct sun and/or strong wind. Do not add water in any circumstances. Apply only to sound, prepared substrates. Do not exceed maximum layer thickness. For waterproofing or damp proofing application, always use at least 2 coats to give a total thickness of between 1.5 to 2.0mm. In areas of severe water penetration, three coats might be required. Protect freshly applied material from freezing conditions and rain etc. SikaTop® Seal-107 ZA does not provide a traffickable finish. Protect with a SikaCem®-810 or SikaLatex® bonded screed. For waterproofing/damp-proofing works, special attention is required to avoid puncturing the waterproof coating with fixings. These must be accommodated by surface bonding with either Sikadur®-31 or Sikaflex® -11 FC etc. When used in contact with drinking structures, ensure that all associated Sika® products and construction materials also comply with the local regulations for drinking water contact.

Curing Details

Curing Treatment	It is essential to cure SikaTop® Seal-107 ZA immediately after application for a minimum of 3 to 5 days to ensure full cement hydration and to minimise cracking. Use polythene sheeting or similar approved methods.

Construction

Notes	All technical data stated in this Product Data Sheet is based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.
Local Restriction	Please note that as a result of specific local regulations the performance of this product may vary from country to country. Please consult the local Product Data Sheet for the exact description of the product uses.

Health and Safety Information

Protective Measures	Cement containing material may cause skin irritation. Wear gloves and goggles or apply barrier cream to hands while working with the mortar.
Ecology	
Transportation Class	
Important Notes	Residues of material must be removed according to local regulations. Fully cured material can be disposed of as household waste under agreement with the responsible local authorities. Detailed health and safety information as well as detailed precautionary measures e.g. physical, toxicological and ecological data can be obtained from the Material Safety Data Sheet.
Toxicity	

Legal Notes

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A4 Cement based FR

Technical Data Sheet
Edition 10.09.09

Construction

Sikalastic®-150

Highly elastic cement based waterproofing coating

Product Description	Sikalastic®-150 is a two-pack elastic fibre-reinforced, cement based flexible waterproofing coating.
Uses	Due to its high elasticity, Sikalastic®-150 is applicable on different structures including those subject to thermal movement and vibration such as: ■ Waterproofing and protection of hydraulic structures like water storage tanks, swimming pools, concrete pipes, bridge parapets, water canals, etc; ■ Waterproofing and protection of external walls to be buried below ground; ■ Internal waterproofing against hydrostatic water pressure of walls and floors in basements and other below ground structures; ■ Waterproofing of terraces and balconies on concrete and old tiles substrates; ■ Protection of exposed and weathered, new and existing concrete surfaces, as a flexible, anti-carbonation, chloride and sulphate resistant coating. Also for sealing of concrete surfaces cracked by plastic and hydraulic surface shrinkage; ■ Elastic coating of precast concrete surfaces, subject to flexural loading and vibration, etc.
Characteristics / Advantages	■ Easy application by metal spatula, roller or flat brush, sprayed, even onto vertical walls and ceiling; ■ Capable of accommodating substrate flexural strains; ■ Crack bridging capability, even on existent cracks or cracks that might open after the product application; ■ Optimum adhesion onto almost all substrate, such as for instance concrete, cementitious mortars, stone, ceramics, bricks and wood. ■ Certified for use in contact with Potable water (AS4020:2005)

Tests

Approvals / Standards	ARPA, Italy: Certificate for drinking water, water permeability (direct & negative pressure), crack bridging; Istituto di Ricerche E Collaudi: Elastic Modulus; Politechnico di Milano: Bonding in immersed conditions (various medias).

Product Data

Form

Colour	Grey
Packaging	Liquid, component A: 6.4 kg Powder, component B: 20 kg

Storage

Storage Conditions / Shelf Life	12 months from date of production if stored in undamaged original sealed containers, in dry conditions and protected from direct sunlight at temperatures between +5°C and +30°C.

Technical Data

Chemical Base	Liquid component: Powder component:	Acrylic emulsion Cement, special aggregates, fibres and additives	
Density	Fresh mortar: 1.7 ± 0,1 kg/l		(EN 12190)
Grading	D_{max}: 0.5 mm		(EN 12192-1)
Layer Thickness	For effective waterproofing: 3 - 4 mm in total (2 mm max per coat)		
Water Penetration under Hydrostatic Pressure	Positive hydrostatic pressure: tested at 0.7 MPa without absorption Negative hydrostatic pressure: tested at 0.1 MPa without leakage		(DIN 1048)

Mechanical / Physical Properties

Bond Strength	~ 0.5 N/mm² (+23°C/50% r.h.)	(EN 1542)
E-Modulus	~ 16.64 N/mm² (+23°C/50% r.h.) (obtained linearizing the initial portion of load/deformation curve)	
Crack Bridging Capacity	1.63 mm (non reinforced concrete, pre-cracked concrete) (+23°C/50% r.h.) 1.57 mm (non reinforced concrete, non cracked concrete) (+23°C/50% r.h.)	

System Information

Application Details

Consumption / Dosage	This depends on the substrate roughness and thickness of layer applied. As a guide, ~ 1.7 kg of Sikalastic®-150 per m² per mm thick. For the recommended thickness of 3 to 4 mm, 1 x 26.4kg unit of Sikalastic®-150 yields covers ~ 3.5 to 5 m².
Substrate Quality	The concrete must be dry, structurally sound, laitance free, clean and free from dirt, oil, grease or other contaminants and loose or friable particles. Tiled surfaces must be free of loose tiles and deteriorated joint.
Substrate Preparation	*Concrete surface:* The substrate shall be prepared by suitable mechanical techniques such as high pressure water jetting, needle guns, grit blasting, hammers, etc. The substrate must be dry or slightly wet. *Tiling floor/walls:* Wire-brush, grind and vacuum the ceramic tiles to remove dust, traces of oils or grease and any other contaminants (the substrate must be dry). *Substrate levelling / repair and pre-treatment:* Large and deep voids and defective areas (honeycombing, broken edges, formwork spacer holes, etc.) shall be repaired with a suitable Sika® MonoTop, SikaTop® mortar (refer to the relevant technical data sheets). For technically correct waterproofing in swimming pools, tanks, basement rooms, etc., corner fillets between the floors and walls shall be made using an appropriate Sika® mortar such as Sika® MonoTop. Joints in concrete, pipe entries, lights and electrical installations in the surfaces must also be sealed by suitable means.

Application Conditions / Limitations	
Substrate Temperature	+8°C min. / +35°C max.
Ambient Temperature	+8°C min. / +35°C max.
Relative Air Humidity	< 75% r.h.
Application Instructions	
Mixing	Sikalastic®-150 shall be mixed with a low speed (< 500 rpm) electric drill mixer. Pour the liquid component A into a suitable mixing container. While stirring slowly, add the powder component B to component A. Mix thoroughly for at least 3 minutes to the required consistency.
Application Method / Tools	*Application by trowel:* Apply the first coat of Sikalastic®-150 using a notched (3x3 mm) trowel, with firm even pressure onto the substrate in order to achieve a regular, consistent thickness. As soon as the first layer has hardened, apply the second coat of Sikalastic®-150 by trowel, taking care to achieve a uniform and continuous layer, which totally covers the first one. Maximum recommended thickness for each coat is 2 mm. In highly stressed areas a special alkali-resistant glass fibre fabric (150 - 160 g/m² and 0.47 mm thick) shall be placed into the first fresh mortar layer. It shall be well trimmed and fully embedded into the mortar avoiding the formation of voids in the coating. To achieve a smooth surface, do not sand or grind the material until it has fully hardened, as this may damage the waterproofing capability. Wait until fully hard and then remove any irregularities in the top surface by grinding as required. *Roller or spray application:* Sikalastic®-150 shall be applied by roller or with suitable mortar spray equipment, applying approximately 2 mm thickness in each coat. Higher thicknesses must be built up in layers and applied when the previous layer is set (hard to the finger nail). Any additional finishing shall then be carried out as above. *Tiling Works:* Ceramic tiles and vitreous tile mosaics can be applied over Sikalastic®-150 using a suitable cementitious tile adhesive (e.g. cement based tile adhesive complying with C2 class as per EN 12004 - cementitious medium-elasticity adhesive). Tile joint shall be filled with the relevant Sikaceram tile grout.
Cleaning of Tools	Tools shall be thoroughly cleaned with water before material setting. Hardened mortar can be only mechanically removed.
Potlife	~ 1 hours at +20°C
Waiting Time / Overcoating	*Immersion:* Sikalastic®-150 must have hardened sufficiently before overcoating or immersion. The following waiting times can be used as a guide:

Action	Waiting time at +20°C	Waiting time at +10°C
Tiling works in horizontal	~ 7 days	~ 14 days
Tiling works in vertical	~ 3 days	~ 7 days
Overcoating with emulsion paint	~ 3 days	~ 7 days
Overcoating with solvented paint	~ 7 days	~ 14 days
Immersion in water	~ 7 days	~ 14 days

Construction

Notes on Application / Limitations	Do not add extra water or other ingredients; each unit must be mixed and used in full. Mixing only parts of units can cause poor particle size distribution and therefore inadequate waterproofing performance; Avoid application in, and protect freshly applied material from direct sunlight and/or strong winds; Sikalastic®-150 hardens more slowly when there is a high environmental humidity level, i.e. in closed or inadequately ventilated rooms and basements; Avoid direct contact with chlorinated swimming pool water by overcoating with a one-component protective coating for swimming pools, or with an appropriate tiled surface; Sikalastic®-150 shall not be applied on wet substrates because this can reduce adhesion or slow the hardening time of the material; Freshly applied Sikalastic®-150 shall be protected from rain for at least 24 hours at 20°C; When overcoating with solvented paints, always carry out preliminary trials to ensure that the solvent does not affect the integrity of the waterproofing layer.
Value Base	All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.
Health and Safety Information	For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.
Legal Notes	The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms and conditions of sale. Users should always refer to the most recent issue of the Technical Data Sheet for the product concerned, copies of which will be supplied on request. PLEASE CONSULT OUR TECHNICAL DEPARTMENT FOR FURTHER INFORMATION.

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A5 Silane/siloxane

Construction

Product Data Sheet
Edition 17/11/2005
Identification no:
02 03 03 01 022 005
Sikagard®-703 W

Sikagard®-703 W

Water repellent impregnation for building facades

Product Description	Sikagard®-703 W is an emulsion, ready for use, silane / siloxane combination based, water repellent impregnation.
Uses	For making facades water repellent and protecting building against water ingress. Sikagard®-703 W can be applied on concrete, mortar, masonry, brick, stone, asbestos cement etc.
Characteristics / Advantages	■ Strong water repellent capability ■ Allows the substrate to breathe (vapour permeable) ■ Treatment is usually invisible not changing the substrate aspect ■ Improves resistance to dirt pick up, and reduces fungal, algal and lichens growth ■ Can be over coated with suitable paints and coatings ■ Ready to use ■ Water based environmental friendly

Tests

Approval / Standards	PV Véritas No. 1108203/2A & 2B, ageing, water vapour permeability, water absorption.

Product Data

Form

Appearance / Colour	liquid	Whitish
Packaging	5 litre and 25 litre containers.	

Storage

Storage Conditions / Shelf Life	12 months from date of production if stored properly in undamaged and unopened, original sealed containers, in dry conditions at temperatures between +5°C and +40°C. Protect from frost.

Technical Data

Chemical Base	Silane / siloxane combination.
Density	~ 1.0kg/l (at +20°C)
pH Value	7 - 10

System Information

Application Details

Consumption	Dependent on substrate porosity: On concrete and mortar: ~ 150 - 200 ml/m^2 On other porous materials: ~ 300 - 500 ml/m^2 (A test is necessary to determine the exact consumption).
Substrate Quality	Clean, sound, free of dust, dirt, oils and grease, efflorescence and old paint coatings etc.. Cracks in concrete more than 200 microns must be repaired first prior to carry out the hydrophobic treatment.
Substrate Preparation	Cleaning should be done with suitable detergent or by light steam or blast cleaning. Best results are obtained on dry, very absorbent substrates. The substrate must look dry with no damp patches.

Application Conditions / Limitations

Substrate Temperature	+5°C min. / 30°C max.
Ambient Temperature	+5°C min. / 30°C max.

Application Instructions

Application Method / Tools	Sikagard®-703 W is applied with a conventional low pressure spray, brush or roller, in a single pass from top to bottom taking care not to let the product run.
Cleaning of Tools	Clean all tools and application equipment with clean water immediately after use. Cured material can only be removed mechanically.
Waiting Time / Overcoatability	Can be over coated with water and solvent-based polymer paints - contact the paint manufacturer for details. For over-coating with Sikagard® emulsion or solvent based coating, wait at least 5 hours after the hydrophobic impregnation.
Notes on Application / Limitations	Cement based substrates (mortar, concrete, etc.) must be at least seven days old. Protect glass surfaces and aluminium frames (possibility of surface damage / staining). Test on a sample surface before use. Cannot be over-coated with lime wash or cementitious coatings. On all substrates, the optimum water repellent capability is achieved after a few days. Water repellency is significantly reduced when the substrate is cracked. Sikagard®-703 W is not suitable for horizontal surface.

Curing Details

Curing Treatment	Sikagard®-703 W does not require special curing but must be protected from rain for at least 3 hours at +20°C.
Notes	All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.
Local Restrictions	Please note that as a result of specific local regulations the performance of this product may vary from country to country. Please consult the local Product Data Sheet for the exact description of the application fields.

Construction

Health and Safety Information

Protective Measures	To avoid allergic reactions, we recommend the use of protective gloves and goggles. In case of contact with skin or eyes irritation can be caused. Seek medical attention immediately if symptom persists. Health and safety advice on packaging labels must be observed.
Ecology	
Transportation Class	
Important Notes	In a liquid state the product contaminates water and must not get into drainage systems and ground water etc. Residues of material must be removed according to local regulations. Detailed health and safety information as well as detailed precautionary measures e.g. physical, toxicological and ecological data can be obtained from the Material Safety Data Sheet.
Toxicity	

Legal Notes

The information, and, in particular, the recommendations relating to the application and end-use of Sika® products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the Product Data Sheet for the product concerned, copies of which will be supplied on request or access on the internet under www.sika.co.za.

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A6 Pure silane

Construction

Product Data Sheet
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Sikagard®-705 L

Sikagard®-705 L

Silane based reactive water repellent impregnation

Product Description	Sikagard®-705 L is a one part low viscosity, solvent free, reactive impregnation for concrete and cementitious substrates based on silane with 99% active ingredient.
Uses	Sikagard®-705 L is used as a water repellent impregnation (Hydrophobic agent) for concrete, mortar etc.
Characteristics / Advantages	■ Excellent penetration ■ Economic and easy to use ■ Reduces capillary water absorption, protection against driving rain and splashing on vertical areas ■ Reduces absorption of water borne contaminants such as de-icing salts and chlorides etc. ■ No change in water vapour permeability ■ Ready to use
Tests	
Approvals / Standards	Conforms to the requirements of LPM: Suitability test to SIA 162/5, Report No. 1-21'699-6.

Product Data

Form		
Appearance / Colour	Liquid	colourless
Packaging	20 kg pail, other sizes can be available on request.	
Storage		
Storage Conditions / Shelf Life	12 months from date of production if stored in unopened, undamaged and original sealed packaging in dry and cool conditions at temperatures between +5°C and +25°C. Protect from moisture.	

Technical Data	
Chemical Base	Silane (99% active ingredient)
Density	~ 0.900 kg/l (at +20°C)
System Information	
System Structure	2 - 3 coats applied ”wet on wet”
Application Details	
Consumption	~ 150 g/m^2 per coat Dependent on absorbency of the substrate and the required penetration depth.
Substrate Quality	Free of dust, dirt, oil, efflorescence and existing paint coatings. Cracks in concrete more than 200 microns must be repaired first prior to carry out the hydrophobic treatment.
Substrate Preparation	Cleaning is best done with suitable detergents or by light blast cleaning, steam cleaning etc. Best results are obtained on dry, very absorbent substrates. The substrate must look dry with no damp patches.
Application Conditions / Limitations	
Substrate Temperature	+5°C min. / +30°C max.
Ambient Temperature	+5°C min. / +30°C max.
Substrate Humidity	5% max.
Application Instructions	
Mixing	Sikagard®-705 L is supplied ready for use and must not be diluted.
Application Method / Tools	Sikagard®-705 L is applied using a low-pressure spray, brush or roller, in a single pass from top to bottom taking care not to let the product run. Apply subsequent coats wet on wet. Avoid ponding on the surface.
Cleaning of Tools	Clean all tools and application equipment with Sika® Kwiklean immediately after use. Hardened / cured material can only be mechanically removed.
Overcoatability	Can be overcoated with water and solvent based polymer paint - contact the proposed paint manufacturer for recommendations. Sikagard®-705 L can be used as a water based primer under many Sikagard® protective coatings. Penetration of water is thus prevented at possible weak spots or in the event of damage to the top coat and the risk of consequential damages such as paint flaking can be reduced. Waiting time: minimum 5 hours, maximum 1 week.
Notes on Application / Limitations	Minimum age of concrete or mortar: at least 4 weeks. Areas such as window frames which still need to be painted, must be securely covered to avoid contact with Sikagard®-705 L. Areas not to be impregnated such as window panes, need to be protected from being accidentally contaminated with Sikagard®-705 L. Sikagard®-705 L can damage some coatings and bituminous products. Sikagard®-705 L can lead to darkening of concrete, apply sample areas first. Cannot be over-coated with limewash or cement paint. The water repellent effect is reduced on horizontal surfaces.

Construction

Curing Details	
Curing Treatment	Sikagard®-705 L does not require any special curing but must be protected from rain for at least 3 hours at +20°C.
Notes	All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.
Local Restrictions	Please note that as a result of specific local regulations the performance of this product may vary from country to country. Please consult the local Product Data Sheet for the exact description of the application fields.
Health and Safety Information	
Protective Measures	Product contains volatile, flammable liquids. Observe relevant regulations concerning health and safety at work. Keep away from ignition sources, refrain from smoking. Use only in well ventilated spaces. Wear protective goggles and gloves made of appropriate plastic material. For more detailed information, please ask for the Material Safety Data Sheet.
Ecology	
Transportation Class	
Important Notes	Must be disposed of as special waste according to local requirements. Residues of material must be removed according to local regulations. Fully cured material can be disposed of as household waste under agreement with the responsible local authorities. Detailed health and safety information as well as detailed precautionary measures e.g. physical, toxicological and ecological data can be obtained from the Material Safety Data Sheet.
Toxicity	
Legal Notes	The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request or access on the Internet under www.sika.co.za.

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Appendix B - All mix results

B1 Mix classification

Table B1: Mix classification for all mixes

Mix #	Parameter									
	Strength (MPa)		OPI (Unitless)		Sorptivity (mm/√hr)		CC (mS/cm)		Porosity (%)	
	Result	Mean	Result	Mean	Result	Mean	Result	Mean	Result	Mean
1	17.8	17.3	9.02	9.03	22.3	20.3	3.30	3.63	12.4	12.1
	16.5		9.06		19.1		3.91		11.7	
	17.6		9.02		19.4		3.68		12.2	
2	13.5	14.2	8.99	9.02	23.0	21.5	4.32	4.02	12.9	13.2
	15.8		9.05		19.2		4.00		13.6	
	13.4		9.02		22.4		3.75		13.2	
3	15.6	16.0	9.09	9.09	18.3	19.2	3.55	3.73	12.8	12.8
	16.4		9.08		18.9		3.92		13.3	
	15.9		9.09		20.5		3.73		12.3	
4	12.6	13.4	9.05	9.04	27.0	25.5	4.80	4.58	12.4	13.7
	13.1		9.10		22.9		4.62		16.3	
	14.4		8.98		26.7		4.33		12.3	

B2 Adhesion testing

Acrylic dispersion

Table B2: Adhesion failure strength and failure mode - acrylic dispersion

Weathering age (Years)	Adhesion strength (MPa)	Failure mode	Mean (MPa)
0	1.42	Concrete/concrete	1.41
	1.30	Concrete/concrete	
	1.51	Concrete/concrete	
3	1.82	Concrete/concrete	1.74
	1.69	Concrete/concrete	
	1.72	Concrete/concrete	
6	1.26	Concrete/concrete	1.26
	1.21	Concrete/concrete	
	1.31	Concrete/concrete	
9	1.11	Concrete/concrete	1.11
	1.14	Concrete/concrete	
	1.08	Concrete/concrete	

Acrylic resin

Table B3: Adhesion failure strength and failure mode - acrylic resin

Weathering age (Years)	Adhesion strength (MPa)	Failure mode	Mean (MPa)
0	1.13	Concrete/concrete	0.99
	0.90	Concrete/concrete	
	0.94	Concrete/concrete	
3	1.30	Concrete/concrete	1.13
	1.27	Concrete/concrete	
	0.83	Concrete/concrete	
6	1.48	Concrete/concrete	1.58
	1.79	Concrete/concrete	
	1.48	Concrete/concrete	
9	1.93	Concrete/concrete	1.85
	1.77	Concrete/concrete	
	1.86	Concrete/concrete	

Cement based

Table B4: Adhesion failure strength and failure mode - cement based

Weathering age (Years)	Adhesion strength (MPa)	Failure mode	Mean (MPa)
0	0.22	Coating/coating	0.21
	0.15	Coating/coating	
	0.25	Coating/coating	
3	0.42	Coating/coating	0.39
	0.33	Coating/coating	
	0.43	Coating/coating	
6	0.45	Coating/coating	0.51
	0.49	Coating/coating	
	0.59	Coating/coating	
9	0.92	Coating/coating	0.87
	0.90	Coating/coating	
	0.80	Coating/coating	

Cement based FR

Table B5: Adhesion failure strength and failure mode - cement based FR

Weathering age (Years)	Adhesion strength (MPa)	Failure mode	Mean (MPa)
0	0.33	Coating/coating	0.38
	0.41	Coating/coating	
	0.39	Coating/coating	
3	0.58	Coating/coating	0.53
	0.60	Coating/coating	
	0.42	Coating/coating	
6	0.71	Coating/coating	0.66
	0.55	Coating/coating	
	0.72	Coating/coating	
9	0.66	Coating/coating	0.71
	0.69	Coating/coating	
	0.79	Coating/coating	