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Literature Review of the Use of Common Protective Coatings for Concrete Structures with Experiences in the South African Context

Final Submission for Minor Dissertation

January 2019

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EXECUTIVE SUMMARY

INTRODUCTION

The main objective of this dissertation is to compile a comprehensive literature review of surface protection systems, including their historical development, specification and use, and to conduct an industry review from the South African market.

With a vast amount of deteriorating reinforced concrete structures and fast developing technology of surface treatments, it is important that engineers have a good working understanding of concrete deterioration, repair and the use of surface protection systems. Additionally, engineers need to have a good understanding of the pore structure of concrete and its transport properties as this is important to understanding the applicability and use of surface treatments (Breysse and Gérard, 1997; Leeming *et al.*, 1997; Ballim, Alexander and Beushausen, 2009).

TRANSPORT PROPERTIES

The movement of ions or fluids in concrete occurs due to four basic mechanism; diffusion, permeation, absorption and migration, as briefly outlined below. The kinetics of movement is broadly governed by the size and nature of the concrete pore structure and its exposure environment (Ballim, Alexander and Beushausen, 2009; Basheer and Barbhuiya, 2010).

Process	**Description**
Diffusion:	Movement of ions, gas or liquid under a concentration gradient
Permeation:	Movement of a fluid through a concrete matrix under an externally applied pressure gradient when saturated with that fluid
Absorption:	Where a fluid is drawn into the pores of concrete through capillary suction
Migration:	Movement of ions due to an electrical potential gradient

Combined transport mechanisms and long-term changes in transport behaviour may need to be considered, Additionally, the size, nature and degree of cracking is an especially important consideration (Ballim, Alexander and Beushausen, 2009).

DETERIORATION OF CONCRETE

Rebar corrosion is the biggest threat to the durability of reinforced concrete structures, and is influenced mainly by the quality of the concrete, its cover depth to the reinforcement and the environmental exposure conditions.

The primary causes of rebar corrosion are carbonation and chloride ingress. Chemical and acid attack may be of concern in certain environments. When using reactive aggregates, alkali-aggregate reaction may also be of concern to unreinforced and reinforced concrete. Surface protection systems can assist in reducing the effects due to the influence of the above penetration processes. Additionally, in harsh environmental conditions, such as in marine areas, additional protection measures are often required to ensure that concrete (existing or new) will not prematurely deteriorate during its service life (Beckett *et al.*, 1987; Technical Committee 60-CSC RILEM, 1988; ACI Committee 201, 2008; Larsen, 2008; Ballim, Alexander and Beushausen, 2009; Gjørv, 2011).

Typically, the following repair techniques may be considered in the repair and service life extension of concrete structures (Mackechnie and Alexander, 2001):

- Crack Repairs
- Patch Repairs
- Surface Coatings
- Migrating Corrosion Inhibitors (MCI's)
- Electrochemical Techniques
- Cathodic Protection
- Demolition and Reconstruction

REPAIR STANDARDS

To ensure that a concrete repair project is successful, a systematic approach to the inspection and repair strategy development needs to be followed (Building Research Establishment, 2000b). The European standard EN 1504 and the Concrete Repair Manual from the American Concrete Institute provides such an approach. South Africa does not have such a standard, but is in the process of adopting the European standards for concrete (South African Bureau of Standards, 2017), EN 206 and EN 1992 – it would thus be highly beneficial for South Africa to move towards the adoption of the EN 1504 code as well.

EN 1504-9 is a very important part of the code, as it provides a structured approach to the investigation of the cause of deterioration and outlines the "Principles of protection and repair." EN 1504-2 covers the use of surface treatment systems, and its provisions are intended to be used as "Methods" in order to cover the "Principles" outlined in EN 1504-9 (Atkins *et al.*, 2009; Raupach and Büttner, 2014).

SURFACE PROTECTION SYSTEMS

Modern technological advances have given rise to numerous surface treatment systems available on the market with various sub-categories that can assist in achieving the durability requirements of a concrete structure, from silanes, siloxanes, many types of polyurethanes and modified cementitious coatings as well as hybrid systems. Each product and system has its use, advantages and disadvantages and the selection of a system and decision on whether to apply a surface treatment or not can be a complicated matter. This decision is often left to the discretion of the engineer, and therefore engineers need to have a good working understanding of surface treatment systems (Leeming *et al.*, 1997; Beushausen and Alexander, 2011; ACI Committee 546, 2014a).

Surface protection systems can be classified according to the way in which the protective action is provided. This is the classification system used by EN 1504 and is divided as follows:

HYDROPHOBIC IMPREGNATION

These are low viscosity fluids which penetrate several millimetres into the concrete and considerably increase the water penetration resistance of concrete, whilst still allowing the passage of water vapour and gases. Typical examples are silanes and siloxanes. They are also referred to as pore lining penetrants (Beckett *et al.*, 1987; Leeming *et al.*, 1997; Bijen, 2003; ACI Committee 546, 2014b).

IMPREGNATION

These are low viscosity solutions that penetrate 1 – 3 mm into the concrete and effectively block pores. They differ from Hydrophobic Impregnations in that they are more restrictive to the passage of water vapour and gases. Typical examples are silicates and silicoflourides as well as certain types of polyurethanes (Beckett *et al.*, 1987; Leeming *et al.*, 1997).

COATINGS

These are treatments that form a continuous protective layer on the surface of the concrete. They are typically 0.1 mm – 5 mm thick, but may be thicker than 5 mm for certain applications. Typical examples are polymer-modified cementitious systems and polyurethanes (Beckett *et al.*, 1987; BS EN 1504-2, 2004).

Surface treatment systems need to meet specified performance criteria. In terms of the concrete durability, these are typically (Beckett *et al.*, 1987):

- Ingress protection
- Moisture control
- Physical resistance / Surface improvement
- Resistance to chemicals
- Increasing resistivity
- Cathodic control

Treatment systems may also be required to bridge cracks, be applied to moist concrete or operate in harsh exposure and weather conditions. Therefore, the selection of a system needs to consider these factors and testing may be required for certain critical properties on-site to determine its suitability. Engineers, owners and suppliers need to collaborate in order to achieve a good solution. EN 1504-2 (2004) provides a detailed list of performance criteria for each of the various types of treatments along with the relevant code of practice for testing.

In general, suppliers recommended application guidelines should be followed in the application of the system.

INDUSTRY REVIEW

A review of products and recent applications from Sika and A.B.E. Construction Chemicals is provided in this work. It was found that polymer-modified systems are still the most commonly used system. Siloxanes are often used for hydrophobic impregnation treatments, as the pure silanes are intended for high-performance usage and are only used in special circumstances. Each of the suppliers provides detailed application guidelines for each of their products as well as generalised expected performance criteria. Many of the products available have been formulated such that they are applicable to a wide range of applications, and it appears that some known problems with certain products have been improved on.

DISCUSSION & CONCLUSIONS

Findings of this report are listed below.

- The selection of a treatment system is a complex issue and therefore requires engineers to have a good appreciation of various surface treatments systems. A proper framework and set of guidelines is needed. Notwithstanding the above, collaboration between the owner, engineer and supplier will go a long way to a successful application.
- South Africa is lacking in the availability of detailed information for engineers to assess, design, specify and monitor treatment systems. South Africa is also in the process of adopting the Eurocodes for concrete design. The EN 1504 repair code contains specific provisions for surface treatments systems and should now be considered for implementation in South

Africa. In the interim, EN 1504 can be used to assist in ensuring a standardised approach has been followed in a repair project.

- The current EN 1504 surface treatment classification divides systems into Hydrophobic Impregnation, Impregnation and Coatings. Whilst these are generally acceptable it may be worthwhile to reconsider Coatings as two types i.e. 'coatings' for thinner coatings and 'overlays' for thicker coatings, as these treatments may function in a very different manner – overlays function by their thickness providing protection and may not be especially complex treatments. They may also simply be applied for levelling and have a treatment or coating applied over them.
- Hydrophobic Impregnation is commonly achieved by the use of silanes or siloxanes or silane-siloxane blends. In particular, silane-siloxane blends are most commonly used. This is due to cost, difficulties in application of silanes, and environmental concerns with the volatile organic compound content of silanes.
- There are conflicting reports on the effectiveness in the use of silicate systems for improving concrete durability. This appears to be in-part due to the lack of agreement on the exact nature of the protection mechanism. Further research is required to reconcile differences in reporting.
- Polyurethanes are very versatile and are available in various forms. Many differences were found in literature on the effectiveness of polyurethanes for improving durability, and sometimes within the same generic type. One of the problems appears to be that researchers often don't describe precisely enough the exact nature of the polyurethane that was used in their works. A standardised reporting approach is needed. However, polyurethanes have been shown to positively effect many durability issues in concrete such as water absorption, chloride diffusion and carbonation – depending on the specific polyurethane used.
- Polymer-modified cementitious coatings are the most commonly available and used surface treatments, and can be used for a wide range of applications. Their exact properties depend on their formulation, type of polymer and polymer-cement ratio. However, they are generally very versatile and most commercially available products can be used to achieve a wide range of properties, including improving the durability of existing concrete surfaces. They are sensitive to weather conditions during curing and special precautions may be required.

LIST OF SYMBOLS, ACRONYMS AND ABBREVIATIONS USED

ACI	American Concrete Institute
ASTM	ASTM International (formerly; American Society for Testing and Materials)
CSH	Calcium silicate hydrate
HCP	Hydrated cement paste
HDI	Hexamethylene di-isocyanate (aliphatic prepolymer)
IPDI	Isophorone di-isocyanate (aliphatic prepolymer)
ISO	International Organization for Standardization
ITZ	Interfacial transition zone
LMC	Latex-modified concrete
MDI	Methylene diphenyl di-isocyanate (aromatic prepolymer)
m-TMXDI	Meta tetramethyl-xylene di-isocyanate (aliphatic prepolymer)
OPC	Ordinary Portland cement
PAE	Acrylic polymers and copolymer
PC	Polymer concrete
PIC	Polymer impregnated concrete
PMC	Polymer modified concrete (also PPCC)
PPCC	Polymer Portland cement concrete (also PMC)
PU	Polyurethane
PUD	Polyurethane dispersion system
PVA	Vinyl acetate homopolymer
RC	Reinforced concrete
RH	Relative humidity
S-A	Styrene-acrylic copolymer
S-B	Styrene-butadiene copolymer
SCM	Supplementary cementitious material
TDI	Toluene di-isocyanate (aromatic prepolymer)
UK	United Kingdom
USA	United States of America
USSR	Union of Soviet Socialist Republic (Soviet Union)
UV	Ultra-violet
VAE	Ethylene vinyl acetate copolymer
VA-VEOVA	Vinyl ester of versatic acid
VOC	Volatile organic compounds
w/b	Water-to-binder (ratio)
w/c	Water-to-cement (ratio)

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1 INTRODUCTION

1.1 BACKGROUND TO STUDY

A durable concrete structure is one which is able to endure the surrounding environmental conditions, over the specified design life, without deterioration leading to loss of serviceability or a need for (major) repair (Ballim, Alexander and Beushausen, 2009).

Modern concrete technology has been in use since the late 1800's, with some structures now well over 100 years old. Initially concrete was seen as a problem-free material requiring almost no maintenance. In the late 1960's, however, durability problems in concrete became apparent as a result of alkali aggregate reaction (AAR), sulphate attack and reinforcement corrosion due to chloride ingress and carbonation in numerous structures. In addition, recently constructed concrete structures appear to be performing even worse compared to older structures, due to (Tilly and Jacobs, 2007):

- Modern designs becoming more economical using less material with higher operating stresses.
- New design details susceptible to corrosion e.g. expansion joints not properly waterproofed causing leakage to underlying concrete.
- Increased emphasis on time and costs in design and construction with competitive tendering, high discount rates and faster construction leading to low quality design, construction and production.
- Use of new concrete technology with unknown durability performance, such as finely ground Portland cement enabling higher early strengths to be achieved producing concrete less tolerant to sometimes mildly aggressive exposure conditions.
- The introduction of de-icing salts during cold weather leading to increased corrosion in highway structures, adjacent buildings, and multi-storey car parks.
- Increased use of concrete in industrial buildings having aggressive environments.

This has led to an increase in repair works to concrete. However, remedial works can be very expensive and disruptive, and have increasingly taken larger portions of the construction budgets worldwide. There is now growing awareness amongst engineers that that there is a need to ensure proper durability provisions in concrete construction and design (Leeming *et al.*, 1997; Tilly and Jacobs, 2007; Dhir *et al.*, 2008).

The most common types of repairs are patch repairs and surface coatings, as evidenced by Tilly and Jacobs (2007). Coatings can also be used for enhancing durability (as well as the appearance) of new structures, particularly required in aggressive environments (Beckett *et al.*, 1987). It is therefore important for engineers to have a good working understanding in the use of concrete surface coatings.

In 1987, the Construction Industry Research and Information Association (CIRIA) (Beckett *et al.*, 1987) published one of the earliest (perhaps even the first) commercially available publications on the use of surface coatings. The technical committee reported that surface coating protection mechanisms were not clearly established and that few standard tests were available to assess performance of surface coatings.

Whilst considerable progress in this field of study has been made, much of the recent understanding and information may not be readily available to engineers, particularly in South Africa. A case in point is that the South African concrete standards do not address the use of surface coatings, nor repairs of concrete in general. Tilly and Jacobs (Tilly and Jacobs, 2007) found that concrete surface coatings were successful only 50% of the time, similarly patch repairs which includes cementitious and polymer-modified materials, was found to be successful 50% of the time.

This points to a need for better guidance and understanding on concrete repair in general and the use of surface coatings in particular.

1.2 PROBLEM STATEMENT AND OBJECTIVES OF RESEARCH

1.2.1 PROBLEM STATEMENT

With continuous aging of vast amounts of existing concrete infrastructure, the need to preserve and maintain them as well as newly constructed infrastructure, surface protection systems are gaining more and more importance.

Most of the information related to the use of surface coatings can be found in specialist literature and may not be easily accessible to most design engineers. Additionally, many design engineers may not be entirely informed of and sufficiently experienced in the use of and specification of protective coatings. Furthermore, with a vast array of different systems and products, considering continuous developments over the past 20 years, keeping up with current understandings, processes and products may be difficult.

There is thus a need to understand the basic principles of the concrete deterioration, repair and the various types of coating systems and products available as well as their uses and limitations. There is also a need to provide some guidelines and standards in the selection and specification of surface coatings by design engineers, so that adequate specifications can be given to contractors and applicators to ensure satisfactory performance of coatings.

1.2.2 OBJECTIVES OF RESEARCH

The main objective of this research study is to compile a comprehensive and detailed literature review of surface protection systems. More specifically, this includes the following objectives:

i. To provide a historical background to the development of this topic over the last 20 years.
ii. To provide a detailed overview of the use of surface protections systems as prescribed in standards and specifications around the world.
iii. To provide common application guidelines and material selection.
iv. To summarise latest research developments in the use of concrete surface coatings.
v. To provide an industry review of the use of protection systems in the South African market.

1.3 SCOPE AND LIMITATIONS

This research forms part of the author's degree programme towards a Masters in Engineering (M.Eng.) in Structural Engineering and Material Science at the University of Cape Town (UCT), South Africa. This research took place between 2016 to 2018 and was submitted on 28 May 2018, for review. The final submission was submitted on 07 January 2019. The research was undertaken under the supervision of Professor H. Beushausen.

This M.Eng. dissertation is considered a minor dissertation worth 60 credits to the degree programme at UCT and has a word limit of 25 000 words. As such background topics and foundational principles could not be discussed in great detail. Important details have been provided where available and was possible under the word limit and references made to detailed sources.

This research study is limited to a literature review and industry review. No laboratory work or site testing was conducted. Some site visits were undertaken to view on-going applications in Cape Town, as mentioned in this report.

1.4 METHODOLOGY

The methodology of this research study contained four main tasks;

1. Undertake a comprehensive literature review on the topic. This includes reviewing the fundamentals contained in existing textbooks and standards and a review of the latest research papers available on the topic.
2. Undertake an industry review. This was accomplished by interviewing various material suppliers accessible in the Cape Town region of South Africa and reviewing their surface coating products. This took the form of both written and oral interviews as well as a few site visits to recently copleted projects. The results of this was retained as a stand-alone record in the Appendix of this document.
3. Analysis and synthesis of knowledge and understanding gained from the above. This includes discussions on various aspects as found in this report.
4. Present findings in this report.

The structure of this reports is as follows;

- An overview of deterioration of concrete structures
- An overview of transport properties of concrete
- An overview of repair of concrete structures and a discussion on repair standards
- A detailed discussion on the use of surface treatment systems
- A detailed review on various types of surface treatments available
- A report on the industry review undertaken as part of this research
- A discussion on the important findings in this research

2 TRANSPORT PROPERTIES OF CONCRETE

The deterioration of concrete (see Chapter 3) relates to the penetrability of the concrete i.e. the ingress of harmful substances (ionic, gaseous or liquid) through the concrete matrix. Understanding the transport properties of concrete is important to predicting (and, by extension, also enhancing) the durability of reinforced concrete structures (Breysse and Gérard, 1997; Ballim, Alexander and Beushausen, 2009).

In this chapter, a brief overview of the important mechanisms and considerations affecting the transport processes in concrete is discussed.

2.1 PORE STRUCTURE AND PENETRABILITY

Durability of concrete is strongly influenced by its penetrability – the extent to which it allows (or disallows) the movement of gases (carbon dioxide and oxygen), liquid (water) or ions (chlorides and sulphates) through its pore structure. Concrete is an inherently porous material and thus transport of substances from its surrounding environment into and through its matrix can occur via diffusion, permeation, absorption or migration (Ballim, Alexander and Beushausen, 2009; Basheer and Barbhuiya, 2010).

The penetrability of concrete is strongly influenced by the pore structure of the concrete (pore size, number, type and distribution). Various types of pores can be present in the concrete, and each will have a different effect on the concrete permeability, as listed below:

- Pores within the hydrated cement paste (HCP)
    - These pores can be further classified into (a) gel pores, (b) capillary pores, (c) hollow-shell pores, (d) air voids. Capillary pores and air voids (due to air entrainment or construction defects) have significant effects on permeability.
- Pores within aggregates
- Pores at the interfacial transition zone (ITZ)
    - These occur at the interface between aggregates and HCP. They generally have a higher porosity and penetrability than the HCP matrix and has a significant effect on permeability. Thus intelligent modification of the ITZ can improve the pore structure and thus durability of concrete (Ballim, Alexander and Beushausen, 2009)
- Capillary voids
- Internal discontinuities in the HCP
- Voids due to construction defects (Basheer and Barbhuiya, 2010)

The main factors influencing the concrete pore structure are:

- The w/b ratio and degree of hydration
    - The concrete pore structure is largely dependent on the w/b ratio and degree of hydration. Figure 1 shows an example of a concrete mix, which demonstrates this principle. As the w/c ratio decreases, so does the porosity, to the point at which full hydration occurs (w/c = 0.4 in this example but may differ depending on the mix design).

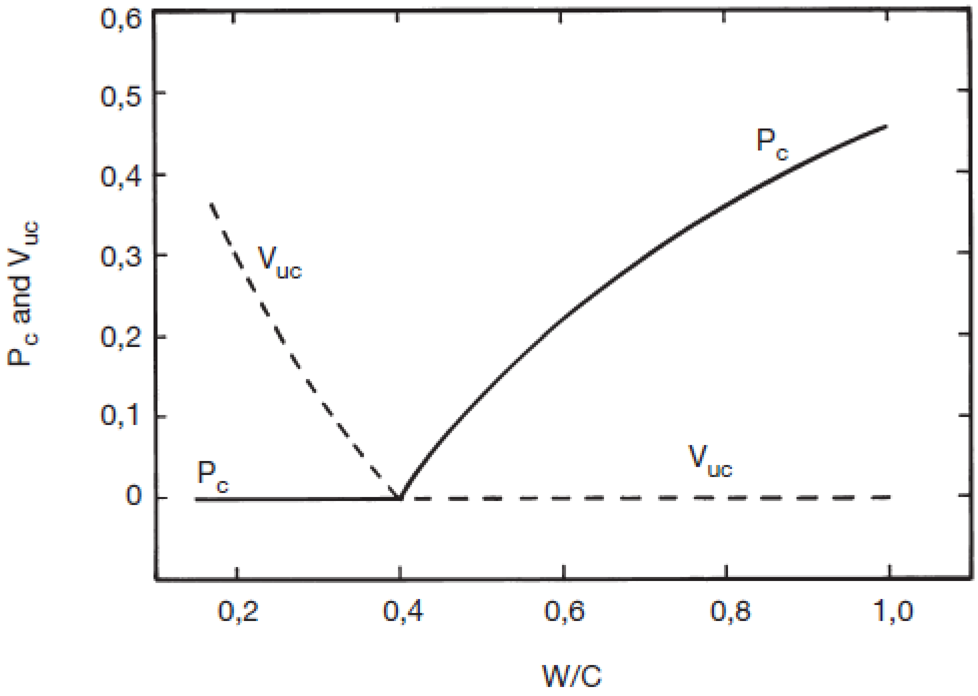

Figure 1: An example of a Concrete's Capillary Porosity (Pc) and Volume Fraction of Unhydratable Cement (Vuc) versus W:C as depicted by Greive (2009)

- Use of supplementary cementitious materials (SCM)
    - The use of SCM's can increase the production of CSH and refine the ITZ and pore structure in general
- Curing regime
- Chemical admixtures used
    - The use of superplasticisers is reported to improve the concrete pore structure due to the change in degree of hydration
- Age of concrete (Basheer and Barbhuiya, 2010)

2.2 TRANSPORT

The movement of ions or fluids occurs due to four basic mechanism; diffusion, permeation, absorption and migration, as discussed below. The kinetics of movement is broadly governed by the size and nature of the concrete pore structure and its exposure environment. Figure 2 below provides an overview of the main factors influencing transport in concrete, modified from Bertolini (2004) as presented by Ballim et al. (2009).

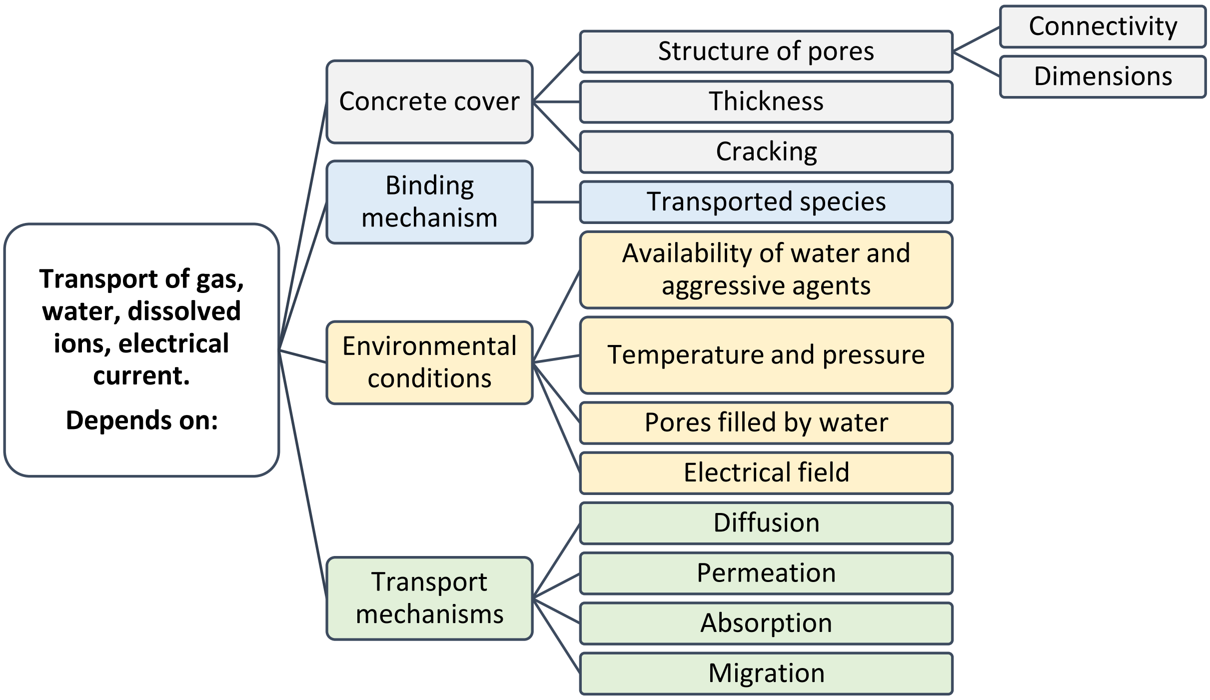

Figure 2: Principal factors in the transport process in concrete, essential in the phenomenon of corrosion [figure is based on information provided by Bertolini (2004) and Ballim et al. (2009)]

These four transport processes are discussed below.

2.2.1 DIFFUSION

Diffusion is the movement of ions, gas or liquid under a concentration gradient. Diffusion can occur in saturated or partially saturated concrete and plays an important role in the migration of chloride ions from sea salts. Diffusion can be either steady state or non-steady state.

Diffusion is a particularly important mechanism of ingress for chloride ions, especially in structures fully submerged in sea water, coastal environments and damp salt contaminated soils. Diffusion also plays a vital role in service-life modelling for these exposure conditions. Exposed concrete surfaces develop high salt concentrations by absorption, due to wetting and drying at the surface. Thereafter diffusion controls the movement to internal areas of lower concentrations, as depicted by Ballim et al. (2009), as shown in Figure 3.

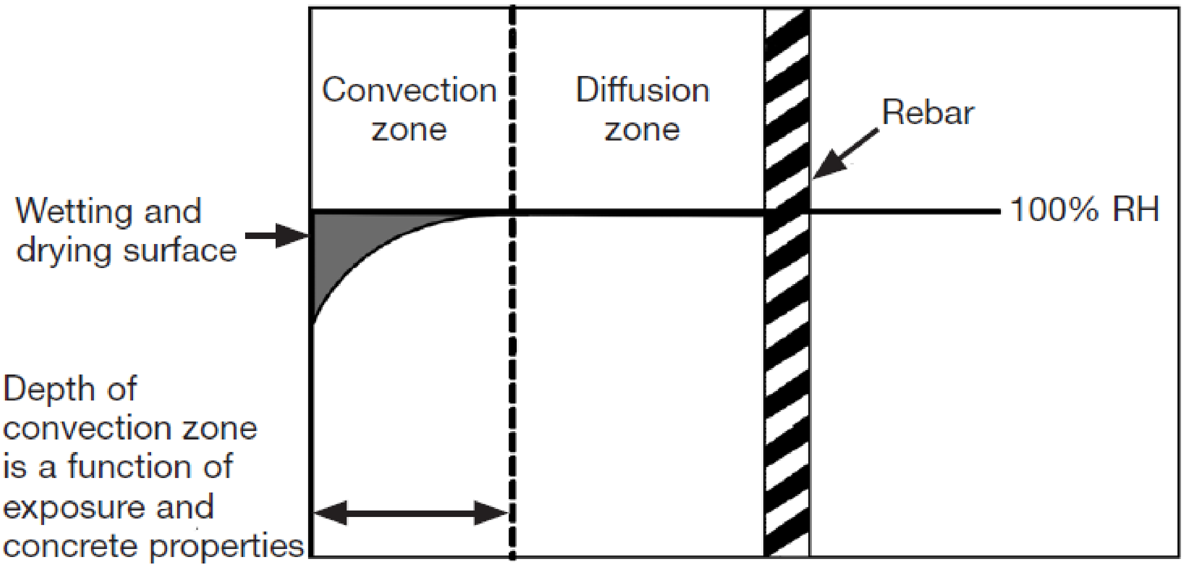

Figure 3: Convection zone in concrete

The rate of diffusion is a function of temperature, moisture content of concrete, type of diffusant and diffusibility of concrete and can be in steady or non-steady state (Ballim, Alexander and Beushausen, 2009). In order to predict the rate of diffusion and thus the durability of a particular structure over time, a service-life model needs to be used. Most service-life models are based on the work by Tuutti (1982) in which a two-stage model, as shown in Figure 4, was developed.

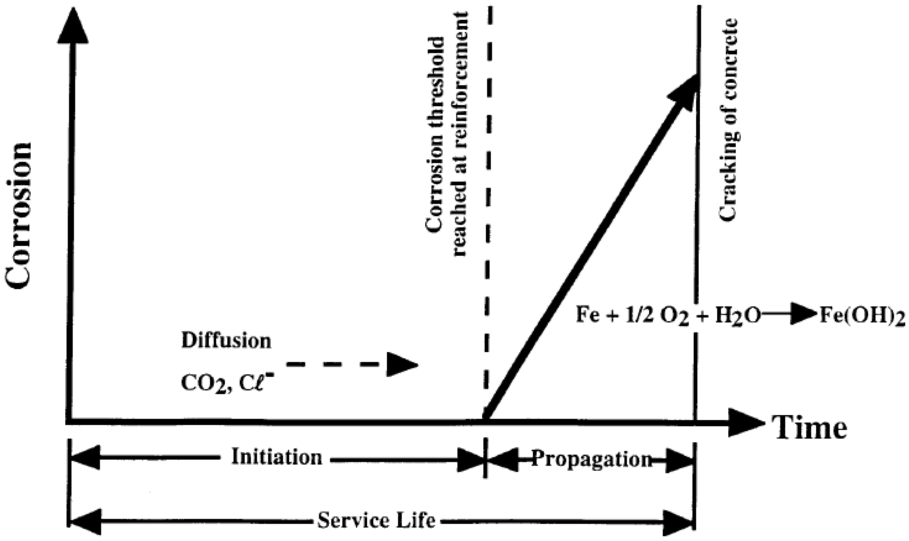

Figure 4: Schematic of conceptual model of corrosion of steel reinforcement in concrete (Tuutti, 1982; ACI Committee 365, 2000)

Using this approach, diffusion of either chloride ions or carbon dioxide can be modelled mathematically using Fick's second law of diffusion (ACI Committee 365, 2000):

$$\frac{\partial C}{\partial t} = D_{eff}\frac{\partial^2 \mathrm{C}}{\partial x^2}$$

$D = Diffusion\ coefficient$

$t = Time$

$C = Concentration\ of\ ions$

$x = distance\ from\ concrete\ surface\ to\ steel\ reinforcement$

The solution to the above equation can be found by Crank's error function as presented by Tuutti (1982), ACI Committee 365 (2000) and Ballim et al. (2009). The purpose here is to present a simplistic overview of how the diffusion process is modelled and the factors affecting it.

2.2.2 PERMEATION

Permeation describes the movement of a fluid through a concrete matrix under an externally applied pressure gradient when saturated with that fluid. Permeability is therefore a measure of the ability of a concrete body to transfer fluids by permeation. Note, however, that some texts use the term 'permeability' as being synonymous with penetrability, as mentioned by Bertolini (2004), since confusion is often not a problem in this case. Permeability of concrete depends on;

- The concrete microstructure,
- The moisture condition of the material and
- The characteristics of the permeating fluids.

Typical examples of this type of action is in deep-water marine structures and the bases of water retaining structures. Permeation can also be used to predict carbonation of concrete (Bertolini, 2004; Ballim, Alexander and Beushausen, 2009; Basheer and Barbhuiya, 2010).

2.2.3 ABSORPTION

Absorption is the process by which a fluid is drawn into the pores of concrete through capillary suction. Capillary action depends on the concrete pore geometry and the degree of saturation of the concrete. Absorption is an important mechanism of ingress near the concrete surface due wetting and drying, becoming less important with depth (Bertolini, 2004; Rostam, 2006; Ballim, Alexander and Beushausen, 2009; Basheer and Barbhuiya, 2010).

2.2.4 MIGRATION

Migration, also referred to as electromigration or accelerated diffusion, is the movement of ions due to an electrical potential gradient. This may occur due to leakage from a direct current supply or, frequently, by the electrical potential due to the (pitting) corrosion process. It is also often used in laboratories for accelerated chloride tests (Bertolini, 2004; Claisse, 2005; Ballim, Alexander and Beushausen, 2009).

This process is treated in some texts as a special case of ingress and often absorption, diffusion and permeation is treated as the three main transport processes.

2.2.5 OTHER CONSIDERATIONS OF TRANSPORT IN CONCRETE

The selection of a single transport mechanism for a particular substance may represent an oversimplification. The effect of multiple simultaneous processes at a given time or depth should be considered. Additionally, transport processes may change over time due to on-going cement hydration, cracking, leaching, chloride binding or general deterioration causing changes to the concrete pore structure. This should be an important consideration for any long-term assessments (Ballim, Alexander and Beushausen, 2009).

2.2.6 CRACKED CONCRETE

The transport properties of cracked concrete behave markedly different to that of uncracked concrete. Cracks interconnect flow paths and act as major pathways for the penetration of water and harmful ions, hastening deterioration. Transport properties of uncracked concrete are generally controlled by the properties of the concrete itself i.e. its porosity. However, in cracked concrete the transport properties depend on the properties of the crack(s), such as crack width, shape, frequency, degree of connectivity and origin of crack. For the purposes of this text it is important to understand that the transport properties of cracked concrete are essential for predicting durability. Further information can be found in specialist literature (Wang *et al.*, 1997; Aldea, Shah and Karr, 1999; Ballim, Alexander and Beushausen, 2009).

2.2.7 TEST METHODS

Basheer et al. (2010) provided a guide to the available test methods for the three main mechanism discussed above, which is reproduced in Table 1 on page 10, and which serves as a good quick reference.

2.3 TRANSPORT PROPERTIES IN RELATION TO CONCRETE COATINGS

These processes (diffusion, permeation, absorption and migration) are important to understand for concrete repairs and in particular, when applying relatively impermeable overlays onto existing concrete. The transport properties of the existing concrete versus that of an applied coating is an important consideration when selecting the type of overlay for a particular application. As an example; large impermeable overlays may trap moisture between the existing concrete and overlay material which will likely fail the overlay (Woodson, 2009).

Table 1: Classification of test methods used to study the transport process in concrete (Basheer and Barbhuiya, 2010)

Absorption	Tests for water absorption capacity			
	Sorptivity	Sorptivity from water absorbed		
		Sorptivity from water penetration depth		
	Absorptivity	Surface absorptivity tests	Initial surface absorption test	
			Autoclam sorptivity test	
			Stand pipe sorptivity test	
		Drill-hole absorptivity tests	Figg water absorption test	
			Covercrete absorption test	
Diffusion	Gas diffusion	Water vapour transmission test		
		Water vapour transpiration test		
		Oxygen diffusion test		
	Ionic diffusion	Steady state diffusion test		
		Non-steady state diffusion tests	Immersion test	
			Ponding test	
		Electric field migration tests	Steady state test	
			Non-steady state tests	Rapid chloride permeability test
				CTH method
Permeation	Liquid permeability	Steady state water flow test		
		Non-steady state water flow test	Steinart guard ring test	
		Water penetration test	Autoclam water permeability test	
	Gas permeability	Constant head gas permeability test		
		Falling head gas permeability tests	Drill hole suction test	
			Drill hole over-pressure test	
			Surface suction test (Torrent Test)	
			Surface over-pressure test (Autoclam air permeability test)	

3 DETERIORATION OF CONCRETE STRUCTURES

3.1 INTRODUCTION TO CONCRETE DETERIORATION

Concrete deterioration has become an increasingly bigger problem in concrete structures. This is evidenced by the extensive damages to bridge decks in North America due to de-icing salts, severe chloride induced corrosion in the Arabian Gulf Area, degradation of concrete sewers due to sulphuric acid and alkali-silica related deterioration in numerous countries worldwide. In particular, South Africa is also reported to have numerous structures that have deteriorated due to reinforcement corrosion induced by carbonation and chloride ingress (Alexander, Mackechnie and Ballim, 1999). Many marine structures in South Africa have been found to exhibit severe deterioration due to rebar corrosion. Investigations have shown that numerous structures along the Western Cape coast of South Africa will require major repairs in order to achieve their original design life (Mackechnie, 2001). This has led to many countries, including South Africa, spending much more money on repairs and rehabilitation of concrete structures than on new concrete structures. Premature deterioration of numerous structures has become a major concern, since it often requires remedial works in order to reinstate the structure to a state of serviceability or safety. This, together with growing urbanisation in many countries, the large number of structures reaching the end of their design life, changing environmental conditions due to climate change, increased sophistication of concrete systems, an increased need to design and construct more sustainable structures and growing pressure from asset owners to design maintenance-free structures, has created a need for engineers to design more durable structures and better maintain existing ones (Pullar-Strecker, 2002; Bijen, 2003; Ballim, Alexander and Beushausen, 2009; Biczok, 2011; Alexander, Beushausen and Otieno, 2012).

Ballim et al. (2009) defines a durable concrete structure or component as one which is able to endure the surrounding environmental conditions, over the specified design life, without deterioration leading to loss of serviceability or a need for (major) repair.

In reinforced concrete structures, rebar corrosion is the biggest threat to concrete deterioration. Deterioration related to rebar corrosion is largely influenced by reinforcement cover (or effective cover), the quality of the cover concrete and the environmental exposure conditions on the component of structure (Beckett *et al.*, 1987; Technical Committee 60-CSC RILEM, 1988; ACI Committee 201, 2008; Larsen, 2008; Ballim, Alexander and Beushausen, 2009; Gjørv, 2011).

In severely detrimental environmental conditions, such as in marine environments, additional protection measures are often required to ensure such structures (or repairs to structures) will not prematurely deteriorate during its service life.

3.2 FACTORS AFFECTING DURABILITY OF REINFORCED CONCRETE STRUCTURES

Factors affecting durability of concrete structures can be categorised into those that cause defects in the concrete itself and those that relate to the corrosion of reinforcement. Defects in concrete can be mechanical, chemical or physical in nature. Those that relate to deterioration of reinforcing steel (corrosion) are carbonation, contamination by aggressive agents (such as chlorides from sea spray) and stray currents (Building Research Establishment, 2000a; Atkins *et al.*, 2009). A shortened schematic of this is shown in Figure 5, below, as presented by Beushausen and Alexander (2011):

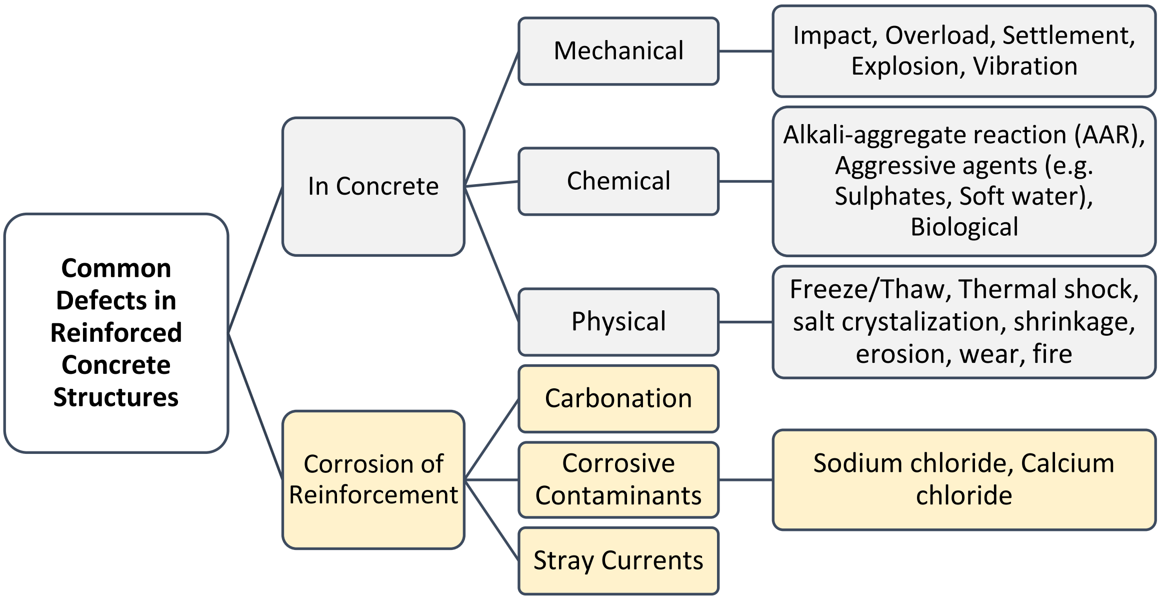

Figure 5: Common causes of defects in RC structures [figure based on information provided by Beushausen and Alexander (2011)]

The following sections discuss the main mechanisms of deterioration on reinforced concrete.

3.3 PRINCIPLES OF CONCRETE DETERIORATION – AN OVERVIEW

3.3.1 CORROSION OF REINFORCEMENT

Reinforcing steel is normally protected by the highly alkaline nature of the concrete pore solution. The pH of ordinary Portland cement concrete systems is 12.5 – 13.5 due to the large amounts of calcium hydroxide ($Ca(OH)_2$) formed during the formation of calcium-silicate-hydrates (CSH). At this pH, a very thin, durable and protective ferric oxide layer (passivating layer) is formed on the surface of the reinforcing steel (the thickness of this layer is in the range of 10^{-9}m). This passivating layer restricts the loss of ferrous ions (Fe^{2+}) to a negligible rate, and will remain and protect the steel from corrosion as long as the pH remains high (above about 9 to 10).

If the alkalinity of the concrete decreases sufficiently, the passivating layer will breakdown and its protective action will be lost and corrosion will ensue. This can occur generally via carbonation of the concrete or locally by the ingress of aggressive agents such as chlorides and sulphate (Building Research Establishment, 2000a; Atkins *et al.*, 2009; Beushausen and Alexander, 2011).

In the corrosion process, anodic and cathodic regions are established along the steel (see Figure 6). At the anode Iron (Fe) is oxidised, while at the cathode oxygen and water is consumed to form hydroxide ions. This then allows the formation of ferrous hydroxide to occur, which is then converted into corrosion products of the form $Fe_2O_3.nH_2O$, also known as rust (see Table 2 below).

Table 2: Corrosion chemical equations

Reaction Location	Chemical Equation
Anode	$Fe \rightarrow Fe^{2+} + 2e^-$
Cathode	${}^{1}/_{2}\,O_2 + H_2O + 2e^- \rightarrow 2OH^-$
Ferrous hydroxide formation	$Fe^{2+} + 2HO^- \rightarrow Fe(OH)_2$

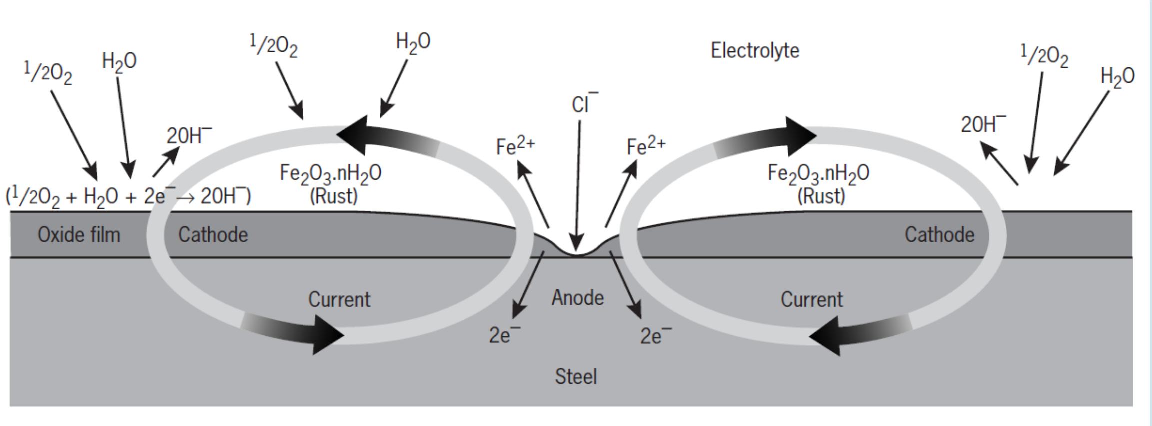

Figure 6: The Corrosion Mechanism (Building Research Establishment, 2000a)

These corrosion products are several times larger in volume than its original parent material. This volumetric expansion sets up internal stress in the concrete, which can later lead to cracking and eventually spalling, once the concrete tensile strength is exceeded (Building Research Establishment, 2000a; Bijen, 2003; ACI Committee 201, 2008; Ballim, Alexander and Beushausen, 2009).

To be noted is that oxygen and water is needed for corrosion to take place. Concrete in dry environments normally show a lower rate and extent of deterioration that concrete in wet or humid conditions. Almost all forms of deterioration involve the presence of water (Ballim, Alexander and Beushausen, 2009). Conversely, in fully saturated (submerged) conditions, corrosion will also be stifled due to the lack of oxygen.

3.3.2 Corrosion due to Carbonation

As mentioned previously, the alkalinity of concrete can be reduced by carbonation. This occurs when atmospheric carbon dioxide diffuses into concrete and reacts with hydrated cement products to form calcium carbonate (see Table 3). This process removes hydroxyl ions from the pore solution and thus reduces the pH. This reduction occurs progressively from the outer surface of the concrete, moving as a front through the concrete. Once it reaches the steel and the pH drops below a value of about 9 to 10, the steel passivating layer is broken down and corrosion is allowed to occur. Figure 7 and Figure 8, below shows carbonation process diagrammatically at different stages (Building Research Establishment, 2000a).

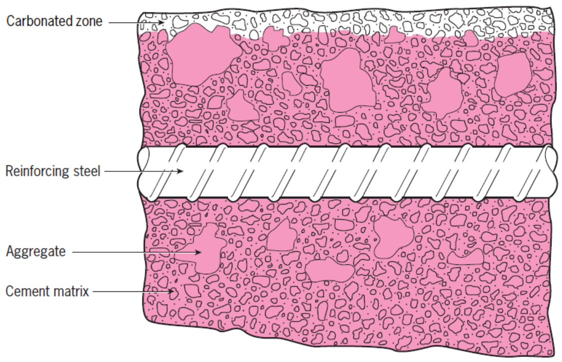

Figure 7: Partially carbonated concrete (Building Research Establishment, 2000a)

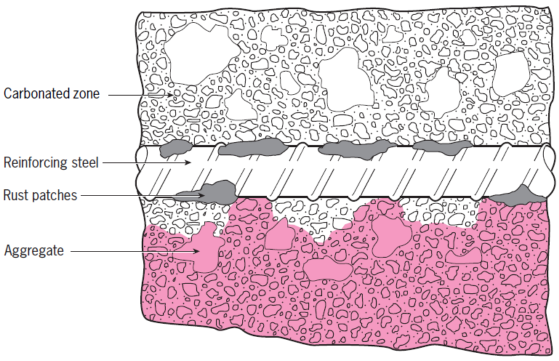

Figure 8: Steel corrosion in carbonated concrete (Building Research Establishment, 2000a)

As mentioned above, for corrosion to actually take place, water and oxygen need to be present in sufficient quantities. Also, the carbonation front is not a distinct line, but rather a zone over which the pH drops from around 13 to 8.3 when all $Ca(OH)_2$ is depleted. Phenolphthalein, commonly used to check the depth of carbonation on concrete specimens, changes colour at a pH of 9.2. Reinforcing steel regains full passivity at about 11.5. Thus, in practice there may be a zone behind seemingly uncarbonated concrete where a risk of corrosion still exists.

Table 3: The carbonation chemical process

1	$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$
2	$CO_2 + 2OH^- \rightarrow {CO_3}^{2-} + H_2O$
3	$Ca^{2+} + {CO_3}^{2-} \rightarrow CaCO_3$

Carbon dioxide diffuses through concrete progressively, but at a decreasing rate. The rate of carbonation is generally given by:

$$x = D \times t^n \quad \textbf{Eqn 1}$$

$Where:$
$x = Depth\ of\ carbonation$
$t = Time\ of\ exposure$
$D = Carbonation\ coefficient$
$n = Depends\ on\ exposure\ conditions. Varies\ from\ 0.4\ to\ 0.5. Generally\ taken\ as\ 0.5$

This is because the carbon dioxide must diffuse through larger distances of the concrete pore solution as well as the already carbonated zone. The carbonation coefficient will largely depend on the quality of the concrete i.e. cement type, w/b ratio, degree of hydration and curing history. For low strength concrete, a carbonation coefficient of 3 – 4 mm/year$^{0.5}$ is possible. As a rough guide, Neville (1995) gives approximate expected values of carbonation depth as;

- 15 mm carbonation penetration after 15 years for a concrete with w/c ratio of 0.6 or
- 15 mm carbonation penetration after 100 years for a concrete with w/c ratio of 0.45.

The rate of carbonation depends on:

- The permeability of the concrete (which is in turn very strongly influenced by the w/b ratio)
- The moisture level of the concrete
- The total alkali content of hydration products

When the concrete pore structure is very dry, no carbonation will take place. When the concrete pore structure is saturated no carbonation will take place as well, because the rate of diffusion of carbon dioxide in water is four orders of magnitude slower than in air. Various texts place the highest carbonation rate to be at slightly different levels of relative humidity (RH), but can conservatively be taken to be in the range of anywhere between 40 – 75%. (Neville, 1995; Building Research Establishment, 2000a; Atkins *et al.*, 2009; Ballim, Alexander and Beushausen, 2009).

It is, however, important to understand that repeated drying and wetting cycles will increase the risk of carbonation. Particularly if there are long drying periods and short wetting periods. During dry periods, carbonation will be promoted (even though corrosion may be limited) and during wet periods corrosion will be promoted (even though carbonation may be stifled). This process over time will lead to higher levels of corrosion due to carbonation (Atkins *et al.*, 2009; Ballim, Alexander and Beushausen, 2009).

Areas of typically high levels of carbonation are car park structures due to its exposure to the atmosphere and exhaust fumes and kitchens and bathrooms in buildings due to the wet-dry cycling process discussed above (Atkins *et al.*, 2009).

3.3.3 CORROSION DUE TO CHLORIDE INGRESS

Along with carbonation, chloride ingress is the other major cause of reinforcement corrosion. Chloride ingress may occur due to:

- The application of de-icing salts on roadways
- Airborne sea-salts in coastal environments
- Chlorides cast into fresh concrete (either by contamination or by using chloride-laden admixtures or aggregates)

Chlorides will diffuse through concrete via the moisture present in the pore structure. Free chlorides present in sufficiently high concentrations, at the surface of the reinforcing steel will cause localised depassivation of the steel and will lead to pitting corrosion. This chloride level is known as the chloride threshold concentration and varies depending on the type of cementitious binder used. It is typically given as 0.4% (by mass of cement) in European literature, but can vary from 0.1 – 1.0% (P. B. Bamforth, 2004).

The chloride threshold depends on a number of factors including concrete cover depth and quality of the concrete cover and the level of saturation of the concrete. The probability of corrosion can be qualitatively assessed by the chloride threshold as presented by Makechnie and Alexander (2001):

Table 4: Qualitative Risk of Corrosion based on Chloride Levels (Mackechnie and Alexander, 2001)

Chloride Content by Mass of Cement	Probability of Corrosion
< 0.4%	Low
0.4% - 1.0%	Moderate
>1.0%	High

A distinction should be made between free chlorides and bound chlorides in the concrete pore structure. A significant portion of chlorides added to the concrete at mixing stage will be bound to the cement hydrates and as such will not normally participate in the corrosion development discussed above. The remaining chlorides will be ‘free’ to stimulate corrosion. To maintain equilibrium, if some free chlorides are removed from the system, some of the bound chlorides may be released and the amount of free chlorides will remain the same. It is therefore important to minimise or eliminate the amount of free chlorides introduced at mixing stage. Accurately measuring free chlorides is difficult. Furthermore, the calculation can be complicated by carbonation or dissolution releasing bounding chlorides, potentially making all chlorides a risk for corrosion (Mackechnie and Alexander, 2001; Ballim, Alexander and Beushausen, 2009).

The rate of chloride penetration from the outside environment is a function of the concrete quality and environmental conditions. The ingress of these chlorides (from outside environment) will chiefly become free chlorides and, as a result, are particularly hazardous to the steel reinforcing (Building Research Establishment, 2000a). In the presence of oxygen, water in the concrete pores and chloride ions above the threshold concentration will cause pitting corrosion to take place, even in highly alkaline conditions. The chloride concentration at the steel level is what mainly controls the risk of corrosion, so that even if chloride ingress from the outside is prevented or limited, a redistribution of chlorides (from a high concentration at some place, to adjacent areas of low concentration) may occur and change the risk of corrosion in different areas (Building Research Establishment, 2000a; P. Bamforth, 2004; Atkins *et al.*, 2009; Ballim, Alexander and Beushausen, 2009).

Additionally, the corrosion risk can also be altered by carbonation of the concrete, which can lead to the decomposition of hydrated chloride salts. This will increase the risk of corrosion, even though the total chloride content remains unchanged (Building Research Establishment, 2000a).

Whichever the method of ingress of chlorides, once the threshold concentration has been reached, corrosion will occur as discussed in Section 3.3.1 and shown in Figure 9, below.

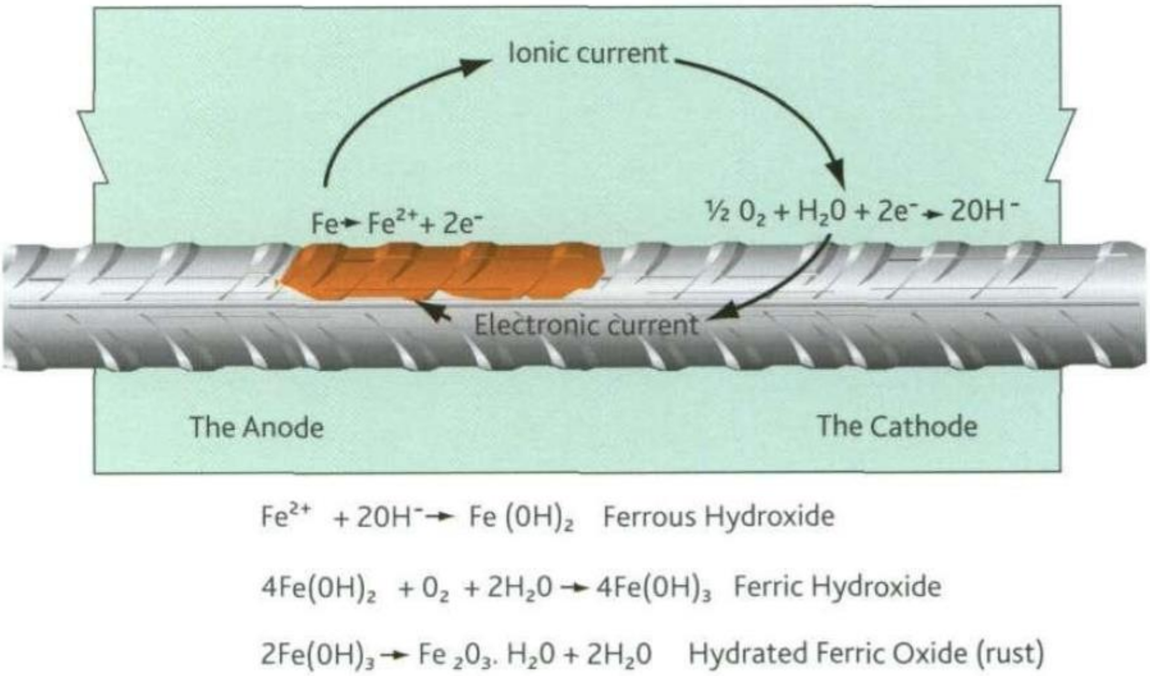

Figure 9: Corrosion Mechanism (Building Research Establishment, 2000a)

3.3.4 Deterioration due to Chemical Attack

In atmospheric and most water and soil conditions, concrete structures will perform satisfactorily. There are however, several types of chemical environments that are harmful to a concrete matrix as well as its reinforcing, if no additional protective measures are taken (ACI Committee 201, 2008). In general, these are (Duchesne and Bertron, 2013; Gambhir, 2013):

- Exchange reactions between aggressive fluids and components of the hardened cement paste, e.g. acid attack.
- Reactions due to the hydrolysis and leaching of the components of the hardened cement paste e.g. soft water attack.
- Reactions involving the formation of expansive products e.g. sulphate attack.

Aggressive agents need to be in solution at some minimum concentration to produce a significant effect. A list of chemicals commonly causing harm to concrete is given by ACI 201.2, as listed in Table 5:

Table 5: Effect of commonly used chemicals on concrete (ACI Committee 201, 2008)

Rate of attack at ambient temperature	Inorganic Acids	Organic Acids	Alkaline Solutions	Salt Solutions	Miscellaneous
Rapid	Hydrochloric Nitric Sulphuric	Acetic Formic Latic	-	Aluminum chloride	-
Moderate	Phosphoric	Tannic	Sodium Hydroxide* >20%	Ammonium nitrate Ammonium sulfate Sodium sulfate Magnesium sulfate Calcium sulfate	Bromine (gas) Sulfite liquor
Slow	Carbonic	- Oxalic Tartaric	Sodium Hydroxide* 10 – 20% Sodium Hypochlorite	Ammonium chloride Magnesium chloride Sodium cyanide	Chlorine (gas) Seawater Soft water
Negligible	-		Sodium hydroxide* < 10% Sodium hypochlorite Ammonium hydroxide	Calcium chloride Sodium chloride Zinc nitrate Sodium dichromate	Ammonia (liquid)

* The effect of potassium hydroxide is similar to that of sodium hydroxide

Factors influencing the durability of concrete in relation to chemical attack is given below:

Table 6: Factors influencing chemical attack on concrete (ACI Committee 201, 2008)

Factors that accelerate or aggravate attack		Factors that mitigate or delay attack	
High porosity due to:	High water absorption. Permeability. Voids.	**Dense concrete achieved by:**	Proper mixture proportioning[*]. Reduced unit water content. Increased cementitious material content. Air entrainment. Adequate consolidation. Effective curing[†].
Cracks and separations due to:	Stress concentrations. Thermal shock.	**Reduced tensile stress in concrete by:[‡]**	Using tensile reinforcement of adequate size, correctly located Inclusion of pozzolan (to reduce temperature rise) Provision of adequate contraction joints
Leaching and liquid penetration due to:	Flowing liquid[§]. Ponding. Hydraulic pressure.	**Structural design:**	To minimize areas of contact and turbulence. Provision of membranes and protective-barrier system(s)[||] to reduce penetration.

[*] The mixture proportions and the initial mixing and processing of fresh concrete determine its homogeneity and density.

[†] Poor curing procedures result in flaws and cracks.

[‡] Resistance to cracking depends on strength and strain capacity.

[§] Movement of water-carrying deleterious substances increases reactions that depend on both the quantity and velocity of flow.

[||] Concrete that will be frequently exposed to chemicals known to produce rapid deterioration should be protected with a chemically resistant protective-barrier system.

Deleterious chemical attack of a concrete matrix can present itself in various forms, such as that due to sulphates, acids, soft water, marine sediments, alkalis and carbonation.

Additional information on chemical attack can be found in the works by Ballim et al. (2009) and Richardson (2002). Additionally, ACI Committee 201's Guide to Durable Concrete (2008) contains codified requirements for protection against various forms of chemical deterioration.

Sulphate and acid attack are discussed briefly below.

3.3.4.1 Sulphate Attack

The classical form of sulphate attack generally occurs with concrete in contact with sulphate-containing soils and groundwater, and sewers. When sulphate ions come into contact with concrete, they react with components of the hardened cement paste (calcium hydroxide and calcium aluminate hydrates) to form expansive products (ettringite and gypsum), thereby deteriorating the cement matrix. Typically, the sulphate resistance of a cementitious binder is related to its tri-calcium aluminate (C_3A) content – Sulphate resisting cements are based on this principle and as such possess low C_3A content (<5% as per ACI201 requirements). Where calcium hydroxide and calcium aluminate hydrates are depleted, the strength imparting calcium silicate hydrates (CSH) components may also be attacked (Richardson, 2002; ACI Committee 201, 2008).

Typical chemicals are sodium, potassium, calcium, and magnesium sulphates. Typical sulphate prone environments are soils, particularly clays and groundwater. Industrial and farming process may also introduce additional sulphates in fluids and soils.

There are three main strategies for dealing with sulphate attack, namely (Skalny, Marchand and Odler, 2002);

1. Ensuring the concrete is of high quality and low permeability
2. Using a sulphate resistant cementitious binder
3. Ensuring the concrete is properly placed and cured

Good sulphate resistance can thus be achieved with a proper understanding of the exposure environment and the mix proportions required to achieve quality of concrete (Skalny, Marchand and Odler, 2002). Although not specifically mentioned by ACI Committee 201, minimizing the ingress and movement of water, that is the carrier of the aggressive sulphate ions, can be achieved by the use of surface coatings.

"Sulfate Attack on Concrete" by Skalny et al. (2002) contains a detailed discussion on the topic.

3.3.5 Acid Attack

The hardened cement matrix in concrete requires a highly alkaline environment to maintain its structural integrity. All the main components of the cement matrix can be dissolved by acids. Concrete thus has a low resistance to acids, although some weak acids may be tolerable, with occasional exposure (Richardson, 2002; Ballim, Alexander and Beushausen, 2009).

There are many exposure environments that cause acid attack, such as certain industrial processes (of concern are old gas works), certain types of farming and in sewers. A particular type of acid attack occurs in seawater exposure. A summary of potentially aggressive acids as well as salts and alkalis is given by Richardson (2002).

Table 7: Effect of Selected Chemicals on Concrete (Richardson, 2002)

Category	Effect on good quality on concrete	
	Disintegration	**Low level of attack**
Acids	Hydrochloric, Hydrofluoric, Muriatic, Nitric, Sulphuric, Sulphurous	Acetic, Carbonic, Carbolic, Humic, Lactic, Phosphoric, Tannic
Salts and Alkalis	Ammonium nitrate	Chlorides of ammonia, copper, iron magnesium, mercury, zinc

Factors influencing the rate of chemical attack include:

- Permeability of the concrete
- pH
- solubility of reaction products
- flow rate of acid
- characteristics of cementitious products
- type of aggregate used
- temperature

When designing for concrete in acidic environments, the rate of attack needs to be reduced to an acceptable level. This is normally achieved through adequate specification of the concrete mix proportions to achieve a dense concrete with a low w/b ratio. Some pozzolanic materials, particularly silica fume, increases acid resistance. The time of exposure to the acid should be minimised where possible and immersion should be avoided (Richardson, 2002; ACI Committee 201, 2008).

Table 1 of BS EN 206-2013 defines three exposure classes XA1, XA2 and XA3, referring to slight, moderate and aggressive chemical environments, respectively. Table 2 of the same code provides a quantitative assessment of these exposure classes for various types of chemicals. However, severe exposure environments require additional means of protection such as surface coatings or sacrificial concrete layers (above that required for structural design) or the use of limestone aggregate or backfill to neutralise the acid. The British standard contains specific advice for dealing with seawater type chemical attack (Richardson, 2002; EN (European Standard), 2013).

3.3.6 DETERIORATION DUE TO ALKALI-AGGREGATE REACTION (AAR)

Aggregates used in concrete are normally inert. However, certain reactive aggregates, especially those containing siliceous minerals, can react with sodium and potassium hydroxides of the concrete matrix, creating expansive products which can lead to cracking and later spalling. This is known as Alkali-Aggregate Reaction (AAR), of which three types have been identified, namely (Richardson, 2002; Oberholster, 2009; Blight and Alexander, 2011);

- Alkali-Silica Reaction (ASR) – This is the most common type and is a particular problem in the Cape Peninsula of South Africa where Malmesbury Group of aggregates is common. ASR describes the reaction between the alkaline pore solution of the concrete and reactive forms of silica in the aggregate, producing an expansive alkali-silica gel.
- Alkali-Silicate Reaction – There is a slight difference between this type and ASR regarding the types of aggregate involved and the nature of the reaction. There is debate about whether this is any different to the basic form ASR, and

- Alkali-Carbonate Rock Reaction (ACR) – this type of AAR involves carbonate aggregate containing clay and dolomite. It is different from ASR in that it does not produce a gel, rather the expansive effect is due to a breakdown of dolomite (dedolomitization), which leads to an increase in moisture and thus swelling of the imbedded clay.

Blight and Alexander (2011) suggests that surface treatment may not be an effective solution without arresting the reaction. If the reaction is allowed to continue, cracking will eventually result within a few years. Due to a lack of understanding of the application of coatings, this has had the lowest rate of success in treating AAR. However, Hobbs (1988) reported collated several works where surface coatings were used to prevent and treat AAR, with mixed results depending on the type of surface coating investigated.

AAR related expansion depends on the amount of removable water, with expansion being directly proportional to removable water above 4% (no expansion occurs below 4%). The main principle of repair of AAR affected structures is to eliminate or minimize its exposure to water. This suggests, at the very least, that AAR can be prevented by the use of surface coatings before the reaction ensues, where it is known that a reactive aggregate is being used (Hobbs, 1988; Blight and Alexander, 2011).

Detailed information of AAR can be found in the works by Blight and Alexander (2011).

3.4 REPAIR STRATEGIES

Several different repair strategies are available for tackling any of the above (or other) deterioration problems. In addition, repair techniques are always improving and new materials and methods are continually being placed on the market. In general, the following repair techniques are commonly available (Mackechnie and Alexander, 2001; Tilly and Jacobs, 2007; BS EN 1504-9, 2008):

- Crack Repairs
- Patch Repairs
- Surface Coatings
- Migrating Corrosion Inhibitors (MCI's)
- Electrochemical Techniques
- Cathodic Protection
- Demolition and Reconstruction

A brief overview of each technique is given below. A more detailed list of techniques can be found in Table 1 of EN 1504-9.

3.4.1 CRACK REPAIRS

These include surface bandaging of cracks, filling of cracks or converting existing cracks into joints. EN 1504-5 contains a detailed information of crack injection. Cracks are repaired to prevent ingress of deleterious agents or to restore structural load bearing capacity. However, care needs to be taken when assessing the cause for the cracks and the need for repair. It is important to understand whether the cause for the cracking remains (live cracks), as this will simply result in further cracking in either the filler used, existing uncracked concrete or the interface between them. Other methods should also be considered as an alternative to or in addition to crack repairs, such as using elastomeric surface coatings (Allen, Edwards and Shaw, 1994; Bijen, 2003; BS EN 1504-9, 2008).

3.4.2 PATCH REPAIRS

Localised patch repair is the most popular type of repair, because they are low cost and provide a temporary aesthetic relief (Mackechnie and Alexander, 2001; Tilly and Jacobs, 2007). The following general steps are followed in patch repairs:

- Remove cracked and delaminated concrete to fully expose the corroded reinforcement
- Clean corroded reinforcement and apply a protective coating to the surface of the reinforcement (e.g. anti-corrosion epoxy coating or zinc-rich primer coat)
- Apply a repair mortar or micro-concrete to replace the damaged concrete
- Optionally, apply a coating to the entire concrete surface to reduce moisture levels in the concrete

It should be noted that patch repairs have very limited effectiveness on deteriorated concrete due to chloride-induced corrosion. Where the surrounding concrete areas are still chloride laden, incipient anode formation may likely occur around the repair – leading to further corrosion and possible failure of the patch repair (Broomfield, 1997; Mackechnie and Alexander, 2001).

Patch repairs are more successful when dealing with areas of localised low cover, before significant chloride penetration has occurred. Once corrosion damage is widespread, removal of all chloride-contaminated concrete in the cover region and beyond the reinforcement will not likely be feasible (Mackechnie and Alexander, 2001).

Patch repair mortars are typically made with polymer-modified cementitious products and may contain fibres, or migrating corrosion inhibitors. These products may also be used as surface coatings. See section 8.4 for a detailed discussion on these products.

3.4.3 SURFACE COATINGS

A wide range of surface coating systems are available, each of which perform different functions. A detailed discussion is provided in Chapters 5 – 8.

3.4.4 MIGRATING CORROSION INHIBITORS (MCI'S)

Migrating Corrosion Inhibitors (MCI's) are chemical substances, usually applied as a coating on the concrete surface, that migrates from the surface of the concrete to the reinforcing steel, reduces the corrosion of the reinforcement without reducing the concentration of corrosive agents. They reduce the rate of the anodic and cathodic reactions by interfering with the dissolution of iron at the anode and disruption of the reduction of oxygen at the cathode (Mackechnie and Alexander, 2001; Büchler, 2005; Beushausen and Alexander, 2011).

MCI's are normally organic materials that move through unsaturated concrete by vapour diffusion. In general, the effectiveness of MCI's is controlled by environmental, material and structural factors as shown in Table 8 (Mackechnie and Alexander, 2001).

Table 8: Likely performance of migrating corrosion inhibitors in concrete (Mackechnie and Alexander, 2001)

Likely inhibition	Corrosive Conditions	Concrete Conditions	Severity of Corrosion
Good	Mildly corrosive, low chlorides or carbonation	Dense concrete with good cover depths (>50 mm)	Limited corrosion with minor pitting of steel
Moderate	Moderate levels of chlorides at rebar (i.e. <1%)	Moderate quality concrete, some cracking	Moderate corrosion with some pitting
Poor	High levels of chlorides at rebar (i.e. >1%)	Cracked, damaged concrete, low cover to rebar	Entrenched corrosion with deep pitting

The effectiveness of MCI's can be improved by the addition of a hydrophobic coating. This approach can be used for both carbonation induced and chloride induced corrosion damage (Mackechnie and Alexander, 2001).

3.4.5 ELECTROCHEMICAL TECHNIQUES

These techniques include electrochemical chloride removal and realkalization, which works by restoring passivating conditions by the temporary application of a strong electric field to the cover concrete region (Mackechnie and Alexander, 2001; Polder, 2005).

Realkalization is a non-evasive process which aims to restore the original alkalinity of carbonated concrete. An anode system with a sodium carbonate electrolyte is placed on the concrete surface and a high current density (typically 1A/m^2) is applied. The resultant electrical field produces hydroxide ions at the reinforcement and moves alkalis into the concrete. Alkaline conditions may be restored in 1-2 weeks (Mackechnie and Alexander, 2001; Beushausen and Alexander, 2011).

Electrochemical chloride removal (ECR) is achieved by applying a direct current between the reinforcement and a temporary electrode placed on the concrete surface. The resultant electrical field causes negatively charged ions to move from the reinforcement to the external anode. This decreases the electrical potential at the reinforcement, increases the hydroxide ion concentration and decreases the chloride concentration at the steel level, restoring passivity (Mackechnie and Alexander, 2001; Beushausen and Alexander, 2011).

ECR is a more time consuming and complex process, taking 4-12 weeks to run. The effectiveness of ECR depends on the extent of chloride contamination, structural configuration (such as spacing and depth of reinforcement), applied current density, time of application, pore solution conductivity, concrete cover resistance and the presence of concrete defects (cracks and delaminations). There is also the possibility of some chlorides being forced deeper into the concrete and there is a risk that unremoved chlorides may diffuse back to the reinforcement and result in further corrosion over time. Thus, the suitability of ECR needs careful assessment (Mackechnie and Alexander, 2001).

3.4.6 CATHODIC PROTECTION

Cathodic protection (CP) systems artificially decrease the electrical potential of the reinforcing steel. This is done by providing a supplementary anode system at the surface of the concrete. An external current is needed between the anode and cathode which is provided either by using sacrificial anodes or an impressed current from an external power source. CP systems have an excellent track record in controlling corrosion (Bentur, Diamond and Burke, 1997; Mackechnie and Alexander, 2001; Polder, 2005).

The use of CP systems requires a specialist to conduct a corrosion survey and perform the design.

3.4.7 DEMOLITION AND RECONSTRUCTION

Where deterioration is far advanced, demolition and reconstruction may be viable. From an economic point of view, this would typically be the last resort as the capital cost, loss of service and temporary cost may well far exceed the cost of repair (Mackechnie and Alexander, 2001).

The extent of corrosion damage to a structure is often over-estimated by engineers, bearing in mind that corrosion damage is normally confined to the concrete cover region. Additionally, engineers with limited experience in repair may well favour demolition and reconstruction due to lack of experience and confidence in the use of various repair systems (Mackechnie and Alexander, 2001).

4 STANDRADS AND GUIDELINES FOR REPAIR OF CONCRETE STRUCTURES

4.1 CONCRETE REPAIR

Costs associated with the repair of concrete structures due to reinforcement corrosion is known to be very high. In addition, the costs for poorly designed or executed repairs works can be even higher. It is therefore important to conduct a proper condition assessment and to follow up with good design, implementation and maintenance (ACI Committee 201, 2008; Beushausen and Alexander, 2011). It is therefore important that engineers understand concrete deterioration mechanisms in order to diagnose problems correctly and have a good working understanding of repair methodologies and principles.

Unless a repair and remediation strategy is developed, there will be little value in any quick-fix remedial works (Building Research Establishment, 2000b). To this end, to ensure that concrete repair projects are successful, it is important to implement a systematic approach to repairs i.e. to conform to a standard code of practice. South Africa has not implemented a concrete repair standard such as the European standard EN 1504 or the American standards compiled as the Concrete Repair Manual. These standards provide the framework for repair projects and allows for standard approaches in the evaluation, design, implementation and maintenance of repair works. In addition, these codes contain a wealth of information which would be useful to engineers and contractors.

The following sections provides a brief overview of the European and American standards, with reference to the South African context.

4.2 CONCRETE REPAIR STANDARDS

4.2.1 AMERICAN STANDARDS BY THE AMERICAN CONCRETE INSTITUTE

The American Concrete Institute (ACI) in collaboration with the International Concrete Repair Institute (ICRI) has produced an extensive library of extremely valuable references, sketches and figures which engineers would greatly appreciate (Springfield, 2009), collated as the Concrete Repair Manual. In addition, ASTM International has a full range of standard tests for concrete repairs products and methods. The *Concrete Repair Manual - 4th Edition 2013* is divided into 2 volumes and comprises 7 principal areas (American Concrete Institute, 2013);

1. General Topics
2. Condition Evaluation
3. Concrete Restoration
4. Contractual
5. Strengthening
6. Protection
7. Special Cases

Selected sub-documents of the Concrete Repair Manual relevant to concrete surface protection and used in this research are listed below:

- ACI 201.1R-08 – Guide for Conducting a Visual Inspection of Concrete in Service
- ACI 201.2R-08 – Guide to Durable Concrete
- ACI 546R-14 – Guide to Concrete Repair
- ACI 546.3R-14 – Guide to Materials Selection for Concrete Repair
- ACI-548.1R-2009 – Guide for the Use of Polymers in Concrete

- ACI-548.3R-2003 – Polymer-Modified Concrete
- ACI-548.4M-2011 – Specification for Latex-Modified Concrete Overlays

The American standards provide an extensive resource for assessing the possible deterioration of concrete structures, the means of repair and, in particular, the use of surface coatings, as evidenced by Springfield's *Review of Manual of Concrete Repair 3rd Ed.* (2009). For the purposes of surface protection systems, ACI 546.3R-14 – Guide to Materials Selection for Concrete Repair is an excellent reference and resource when considering, selecting and specifying a surface treatment system. It contains information on concrete overlays, crack repairs, a range of different surface coatings including references and diagrams to ASTM, European codes and International Organization for Standardization (ISO) tests relevant to the various material properties (such as chloride ion absorption, water vapour permeability, carbon dioxide diffusion, hardness etc.) and recommendations for test requirements. It also contains information on current industry concerns.

However, South Africa has historically largely based its structural codes of practice on those from the United Kingdom (UK), and as such, is more favoured to that of the original British Standards and the now current Eurocodes. South Africa stands to benefit greatly from the adoption of the Eurocodes and is, in fact, currently in the process of adopting the Eurocodes (EN 1992) for concrete design and materials specification (EN 206) (Institute of Structural Engineers and South African Institution of Civil Engineering, 2008). From a south African perspective, it would therefore be sensible to discuss concrete repair in light of the European repair standard; *EN 1504 Products and systems for the protection and repair of concrete structures - Definitions, requirements, quality control and evaluation of conformity*.

4.2.2 CONCRETE REPAIR AND THE ADOPTION OF EUROPEAN STANDARDS IN SOUTH AFRICA

EN 1504 (2004) provides a comprehensive overview for repair, rehabilitation and protection of concrete structures (Raupach and Büttner, 2014). Part 2 of the EN 1504 standard also specifically provides requirements of "*products and systems to be used for surface protection of concrete, to increase the durability of concrete and reinforced concrete structures, as well as for new concrete and for maintenance and repair work.*" Such a standard need to be followed in the execution of repairs, particularly on major structures.

The South African concrete design codes, specifically *SANS 10100-2 Structural use of Concrete Part-2: Materials and execution of works* has provisions for durability requirements, but is still lacking in many aspects (Kessy, Alexander and Beushausen, 2015). There are no South African standards or official guides on concrete repair, let alone surface protection systems. The Concrete Institute of South Africa has published some leaflets on minor repairs and some basic information on cementitious materials, but these are small 5 – 10-page documents, which are simply intended to keep the public informed about developments in concrete.

SANS10100-2 has recently been replaced by *SANS 50206:2015 Concrete — Specification, performance, production and conformity*, which is the identical implementation of *EN 206:2013 Concrete - Specification, performance, production and conformity*, and is the first step to the full implementation of the Eurocodes (for concrete). To be noted is that SANS 10100-1 will also soon be replaced with a revised code *SANS 51992 Design of concrete structures – Part 1-1: General rules and rules for buildings* which will be a supplement document to *EN 1992-1-1:2004*, according to the SABS Programme of Work of 15 December 2017 (South African Bureau of Standards, 2017).

This step paves the way for the adoption of other European concrete codes in general, and particularly, in future, the possibility of the adoption of the EN 1504 standard. Therefore, EN 1504 has been used in this work as a basis on which to explore, discuss and categorise surface protection systems.

4.3 OVERVIEW OF EN 1504 IN RELATION TO SURFACE PROTECTION SYSTEMS

EN 1504 is divided into 10 parts. *Part 9 General principles for the use of products and systems* is an important part of the code as it provides a structured approach to the investigation of the cause of deterioration. It also outlines 11 "*Principles of protection and repair.*" *Part 2 Surface protection systems for concrete* provides specifications for products and systems for the repair and protection of concrete structures. The provisions of EN 1504-2 are intended to be used as "*Methods*" in order to cover the "*Principles*" outlined in EN 1504-9 (BS EN 1504-2, 2004; BS EN 1504-9, 2008; Atkins *et al.*, 2009).

The first six Principles, as set out by EN 1504-9, covers the protection and repair of defects in concrete, generally caused by mechanical actions, chemical and biological actions, physical actions and fire. Principles 7 – 11 relate to the protection and repair of defects caused by reinforcement corrosion, in particular; physical loss of the protective concrete cover, carbonation, contamination by corrosive agents (usually chloride ions) and stray currents. This is summarised in Table 9.

Table 9: Repair principles in BS EN 1504 Part 9 (Atkins et al., 2009)

Principles Related to Defects in Concrete		
Principle 1	[PI]*	Protection against ingress
Principle 2	[MC]	Moisture control
Principle 3	[CR]	Concrete restoration
Principle 4	[SS]	Structural strengthening
Principle 5	[PR]	Increasing physical resistance
Principle 6	[RC]	Increasing resistance to chemicals
Principles Related to Reinforcement Corrosion		
Principle 7	[RP]	Preserving or restoring passivity
Principle 8	[IR]	Increasing resistivity
Principle 9	[CC]	Cathodic control
Principle 10	[CP]	Cathodic protection
Principle 11	[CA]	Control of anodic areas
*Brackets indicate EN 1504 abbreviation		

Of the above protection and repair principles, five can be achieved with surface treatments, as outline in EN 1504-9 and EN 1504-2, and summarised in Table 10.

Table 10: Principles and Methods of Protection and Repair (Shaw, no date; Bijen, 2003; BS EN 1504-2, 2004; BS EN 1504-9, 2008)

Protection / Repair Principle	Method of Protection that can be used
Principles and methods relating to defects in concrete	
1. Protection against ingress [PI]	1.1 Hydrophobic Impregnation [H] 1.2 Impregnation [I] 1.3 Coating [C]
2. Moisture control [MC]	2.1 Hydrophobic Impregnation [H] 2.2 Coating [C]
5. Increasing physical resistance [PR]	5.1 Coating [C] 5.2 Impregnation [I]
6. Resistance to chemicals [RC]	6.1 Coating [C]
Principles and methods relating to reinforcement corrosion	
8. Increasing resistivity [IR]	8.1 Hydrophobic Impregnation [H] 8.2 Coating [C]

Whilst the above 5 principles are specifically mentioned in EN 1504-9 for surface treatments, it may be possible to tackle Principle 9: Cathodic Control by limiting oxygen content with a surface coating [C] and Principle 11: Control of Anodic Areas with applying a corrosion-inhibitor [I] to the concrete surface (Bijen, 2003).

5 SURFACE PROTECTION SYSTEMS – AN OVERVIEW

5.1 INTRODUCTION

The need for providing additional protection to concrete structures, particularly in aggressive environments is now well established (Almusallam *et al.*, 2003). There are numerous strategies that can be used to ensure a concrete structure will meet its durability service-life requirements and prevent premature deterioration. Many such materials and systems are available on the market and claim to be beneficial in corrosion prevention and protection (Beushausen and Alexander, 2011).

Systems and materials available to Engineers for use as surface protectants vary widely, from silanes, siloxanes, silicones, epoxy resins, polyurethanes and modified cementitious coatings to hybrid materials. The decision to apply a surface protectant (or not) and which system to use is left to the discretion of the responsible engineer. As such, engineers need a good working understanding of deterioration principles and the functioning of the various systems available (Beushausen and Alexander, 2011; ACI Committee 546, 2014a).

Each product and system has its advantages and disadvantages, and deciding which system and material to use on a particular project (or whether to use them at all) can be a complicated matter. In addition, within one generic type of system or material properties and resulting effects can vary (Leeming *et al.*, 1997).

The American Concrete Institute (ACI Committee 546, 2014a) defines protective treatment as "*materials and methods which extend the service life of concrete structures by reducing their exposure to moisture and other factors, reducing corrosion of metals embedded in concrete, increasing surface abrasion or impact resistance, or improving the structure's resistance to other deleterious influences*".

The selection of a surface treatment is, thus, a complex matter for the following reason (Leeming *et al.*, 1997):

- Service requirements and cost constraints can vary from one project to the next.
- A surface treatment may need to achieve several outcomes at once, such as limiting ingress of chlorides and maintaining aesthetics.
- The surface treatment may need to withstand varying climatic conditions.
- Products of the same formulation can vary significantly between products. And different products can perform to varying levels of performance within one generic type.
- They may be expected to perform given ill-defined or varying site conditions.
- An assortment of test procedures exists for different performance characteristics and universally agreed-on performance criteria may not exist.
- In-service performance data is not easily available and the relationship between laboratory tests and actual on-site performance can be difficult to assess.
- Health and safety requirements may limit the choice of protection system.

Additionally, it is imperative that the design engineer gives an unambiguous specification so that the contractor has a clear idea of the project requirements. It is therefore important that Engineers have a basic understanding of the products, materials and systems available in order to provide adequate specifications.

5.2 CLASSIFICATION OF TREATMENT SYSTEMS

A large variety of systems and products exist which provide a wide variety of functions at varying degrees of performance. Often performance between products of the same generic type can also vary, making classification somewhat difficult. Three classification systems have been used in literature (Beckett *et al.*, 1987; ACI Committee 546, 2014a). These are, classification by:

1. The way in which the protective action is provided
2. The basic form of the material and curing method
3. Chemical composition

Whilst a classification by chemical composition initially appears to be a logical choice, as some materials offer specific types of functionality, the variety of products available together with new technological advances and the expertise of formulators allows for the production of materials of the similar chemical composition to have very different properties – such that classification by chemical composition offers little insight into the expected performance of the material. Becket et al. (1987) used both a classification by protective action, and a classification by the basic form of the material and curing method.

Similarly, Leeming et al. (1997) also used a classification by protective action and acknowledged that the use of a classification system by chemical composition provides little information on expected performance due to the variety of properties one type can possess.

5.2.1 CLASSIFICATION BY BASIC FORM OF MATERIAL AND CURING METHOD

Classification by the basic form of the material and method of curing, however, may be a useful classification, as it describes the nature of the coating material and how it solidifies to form a barrier, and so a brief overview is given below.

The form of the material can be:

- **Solvent Free** – These generally cure by chemical reaction, reaction with the substrate or oxidation. Examples are silicones, silanes, siloxanes (may be solvented), epoxy resins and drying oils.
- **Solvented** – These are normally 'spirits' or thinners and are blends of aliphatic and aromatic hydrocarbons, ketones, alcohols and glycol esters. An example is resins.
- **Dispersants** – Emulsions fall into this group. Water is a common dispersant of modern paints.

And the method of curing can be;

- **Reaction with the substrate** – Examples are silanes and siloxanes.
- **Reaction within the film** – This is typical of two-pack materials. Examples are epoxies and polyurethanes.
- **Reaction with moisture** – Examples are polyurethanes and silanes.
- **Oxidisation** – Materials which react with atmospheric oxygen to solidify. Linseed oil and other oleo-resinous materials are examples.
- **Loss of solvent or dispersant** – Most surface treatments cure in this method.

Although not immediately useful, this method does provide a basic background understanding of various types of products, and so, is shown, in Figure 10, below.

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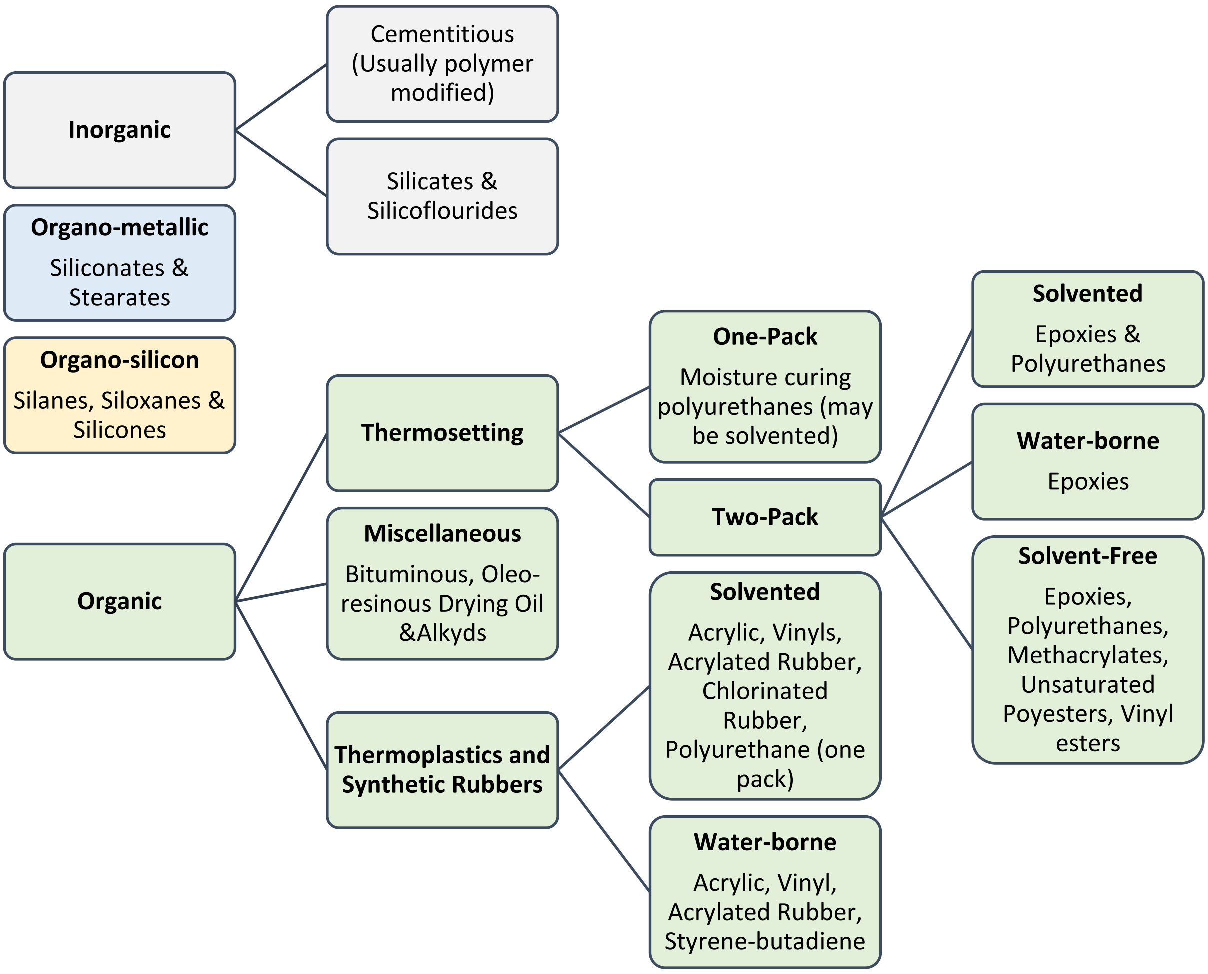


Figure 10: Classification of Surface Treatments by Main Generic Material [Redrawn according to Leeming et al. (1997)]

5.2.2 CLASSIFICATION BY TYPE OF PROTECTIVE ACTION

The American Standard ACI 546R-14 and the European Standard EN 1504-9 classifies coatings by their protective action, albeit with slightly different boundaries. This method of classification is the most intuitive method and provides an easy way to understand potential products that should be considered.

Table 11 shows the terminology used for surface treatment classifications by various authors and standards, compared to the EN 1504 equivalent. Leeming et al.'s classification is essentially the same as that in EN 1504, although different terminology is used. Beckett et al.'s classification includes an additional category 'Sealers' which is classed as somewhere between 'Penetrant pore-blockers' and 'Coatings', and essentially can be considered very thin coatings. ACI 546R-14 classes the silane and siloxane type treatments under 'Penetrating Sealers', which falls under the category of 'Hydrophobic Impregnation' in EN 1504 terminology. Whilst the other three authors included silicate type products under 'Impregnation', ACI 546R-14 does not discuss silicate treatments. They do, however, discuss 'Surface-Applied Corrosion Inhibitors' and has been included here since they do penetrate concrete, and do not form coatings on the concrete surface. The use of corrosion inhibitors is a specialised technology and is only mentioned in brief here to denote classification.

Table 11: Classification by Protective Action by various Authors and Standards

EN 1504-2 (2004)	**ACI 546R (2014)**	**CIRIA Technical Note 130 (1987)**	**Concrete Society Technical Report 50 (1997)**
Hydrophobic Impregnation	Penetrating Sealer	Penetrant Pore-Liner	Pore-Lining Penetrants
Impregnation		Penetrant Pore-Blocker	Pore-blocking Sealers
	Surface-Applied Corrosion Inhibitor		
Coatings	Surface Sealers	Sealers	Surface Coatings
	High-build Coatings		
	Elastomeric Coatings	Coatings	
	Overlays*		

*Overlays are outside of the scope of this thesis
(Beckett *et al.*, 1987; Leeming *et al.*, 1997; BS EN 1504-2, 2004; ACI Committee 546, 2014a)

A definition of each of the terms used by EN 1504 is provided in Table 12 below (BS EN 1504-2, 2004; BS EN 1504-1, 2005). The brackets indicate the abbreviation used by the Standard.

Concerning the three classes in EN 1504, the author feels that it would be useful to have a fourth category 'Overlays' as has been done in the ACI 546 Standard, to differentiate between coatings of say 0.1 mm – 5 mm (to be classed as Coatings) and those greater than 5 mm (to be classed as Overlays). Note 1 under the definition of Coatings (section 3.3.5) of EN 1504-1 states the following:

"NOTE 1: Thickness is typically of 0,1 mm to 5,0 mm. Particular applications may require a thickness greater than 5 mm."

This appears to suggest that 'Coatings' of thickness greater than 5 mm are special types of 'Coatings' and supports the author's proposal. Additionally, 'Overlays' would typically include very different types of systems such as mortar rendering and polymer modified cement mortars and may be used for patch repairs, which is very different from the polyurethanes, elastomeric coatings and other such coatings. Overlays may also have a surface coating, from one of the other material classes, applied over it for protection.

Table 12: EN 1504-1 Surface Treatment Classes

Treatment Class	Definition	Examples
Hydrophobic Impregnation [H]	Treatment of concrete to produce a water-repellent surface. The pores and capillaries are internally coated, but they are not filled. There is no film on the surface of the concrete and there is little or no change in its appearance	Silanes Siloxanes
Impregnation [I]	Treatment of concrete to reduce the surface porosity and to strengthen the surface. The pores and capillaries are partially or totally filled	Organic polymers
Coatings [C]	Treatment to produce a continuous protective layer on the surface of concrete	Organic polymers Organic polymers with cement as a filler Hydraulic cement modified with polymer dispersion

A schematic of the functioning of these classes is shown in Figure 11 below, where (a) represents Hydrophobic Impregnation, (b) and (c) represent Impregnation (showing partial and full filling of pores, respectively) and (d) falls under Coatings.

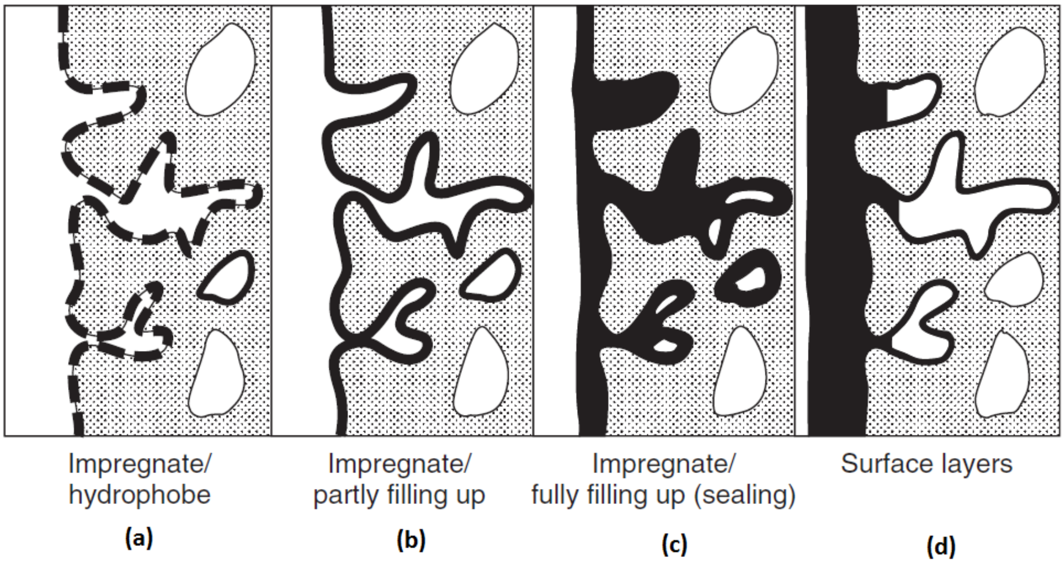


Figure 11: Types of Surface Protection Systems (Bijen, 2003)

5.3 ASSESSMENT BEFORE APPLICATION OR REPAIR

It is of vital importance to understand the cause of deterioration and extent of damage before any repair works are started, and before any surface protection systems are specified. A thorough condition assessment is therefore necessary and is in fact a requirement of EN 1504-9 (Building Research Establishment, 2000b; Broomfield, 2010; Beushausen and Alexander, 2011). As a guide and a minimum requirement, EN 1504 requires the assessment to include;

- The visible condition of the existing concrete structure;

- Tests required to determine the condition of the concrete and reinforcing steel;
- The original design approach;
- The environmental exposure, and type of contamination;
- The history of the concrete structure;
- The conditions of use, (e.g. loading or other actions);
- Requirements for future use.

Figure 12 and Figure 13 show how a repair and remediation strategy may be developed and the diagnostics steps that need to be undertaken, as required by EN 1504-9.

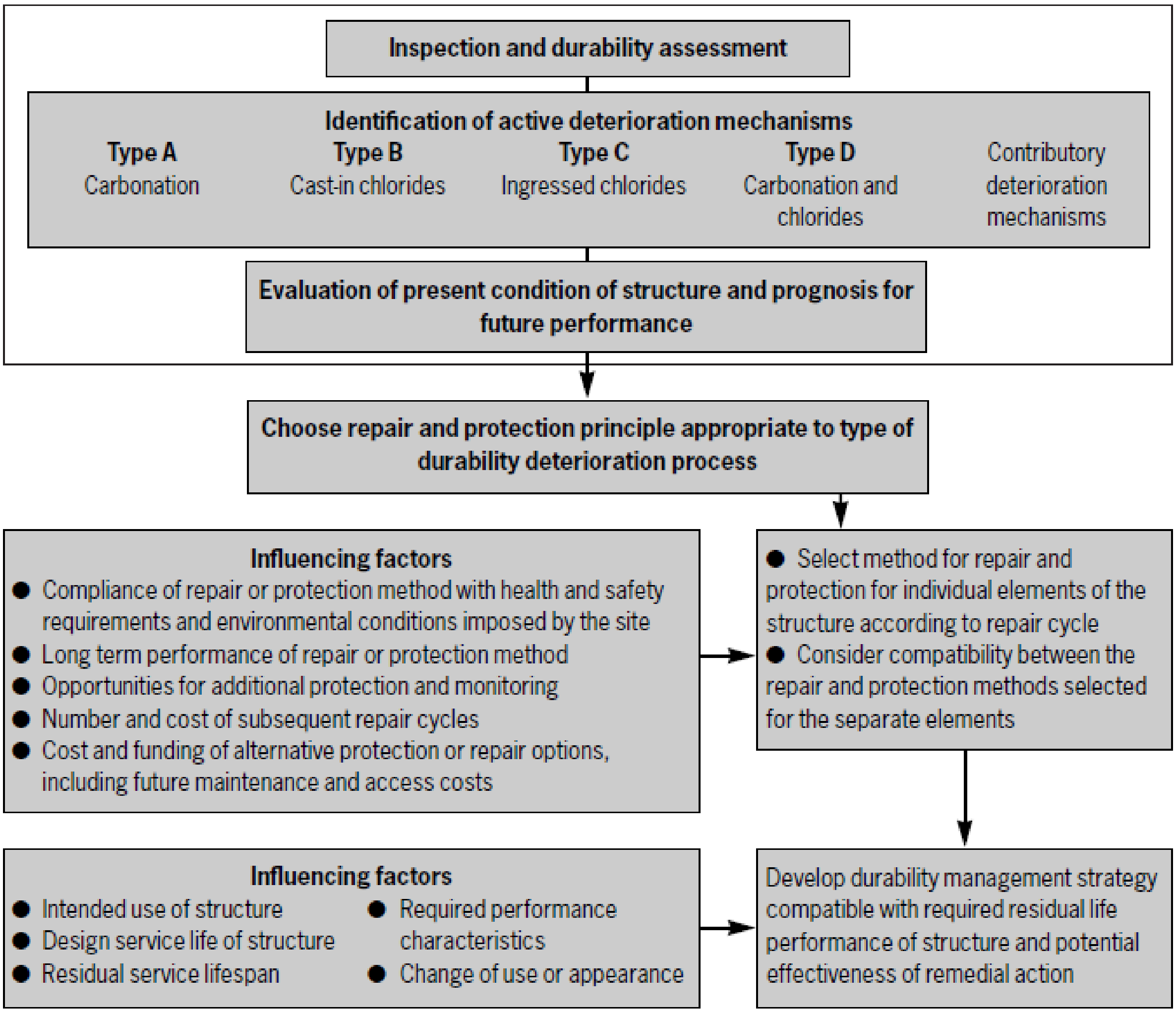


Figure 12: Development of a strategy for the repair and protection of steel reinforced concrete (Building Research Establishment, 2000b)

Minimum requirements for assessment of defects and their causes →

- Present condition
- Original design approach
- Environment and contamination
- Conditions during construction
- Conditions of use
- History of structure
- Future use

↓

Choose repair and remediation options →

- Do nothing for now and monitor
- Reanalyse structural capacity
- Prevent or reduce further deterioration
- Improve, strengthen or refurbish all or part
- Reconstruct all or part
- Demolish all or part

→

- Intended use, design service life
- Required residual life performance characteristics
- Long-term performance of protection or repair works
- Additional protection and monitoring
- Number and cost of subsequent repair cycles
- Cost and funding of alternative protection or repair options, including future maintenance and access costs
- Properties and methods of preparation of existing substrate
- Appearance of protected or repaired structure

↓

Identify principle of repair appropriate to the repair and remediation options →

Principles and methods of remediation

Defects in concrete	*Reinforcement corrosion*
1 Protection against ingress	**7** Preserving or restoring passivity
2 Moisture control	**8** Increasing resistivity
3 Concrete restoration	**9** Cathodic control
4 Structural strengthening	**10** Cathodic protection
5 Physical resistance	**11** Control of anodic area
6 Resistance to chemicals	

↓

Choose a method →

- Appropriate to type and cause or combination of causes and to the extent of the defects
- Appropriate to future service conditions
- Appropriate to protection or repair option chosen
- Compliance with the principle chosen
- Availability of products and systems which comply with the EN 1054 series or any other relevant EN or European Technical Approval

↓

Choose materials which comply with EN 1504-9 →

- Characteristics for all intended uses
- Characteristics for certain intended uses
- Characteristics may be considered for specific applications

↓

Set out inspection and maintenance requirements →

- Record of the protection or repair works which have been carried out
- Instructions on inspection and maintenance to be undertaken during the residual life of the repaired part of the concrete structure

Figure 13: Overview of repair and remediation process and options as defined in EN 1504-9 [redrawn from Building Research Establishment (2000b)]

5.4 REASONS FOR THE USE OF SURFACE TREATMENTS

Concrete surface treatments can be used to achieve a range of different functions including appearance enhancement, mechanical and physical resistance as well as those functions related to reinforced concrete deterioration, such as chloride ingress, carbon dioxide and oxygen ingress.

A list of possible functional properties that surface treatments can control is provided in Table 13 below (Leeming *et al.*, 1997):

Table 13: Possible Properties that Surface Treatments can Control (Leeming et al., 1997)

Appearance	Chemical Resistance	Ingress Control	Mechanical & Physical Resistance
Colour	Sulphates	Chlorides*	Freeze/Thaw
Texture	Acids	Carbon Dioxide*	Salt Crystallization
Opacity	Chemicals e.g.	Oxygen*	Abrasion
Cleanability	- Brewery products	Water Penetration	Impact
Graffiti	- Dairy Products	Water Vapour	Anti-Skid
Reflectance	- Slurry Tanks	Moisture Control;	Static & Spark Risk
Mould Growth		Drying	
		ASR	
		Methane	
		Radon	
*in relation to corrosion of reinforcement			

Surface treatments are primarily used to provide a barrier against (or control the ingress of) deleterious agents. Regarding reinforcement corrosion these can be:

- Controlling the rate of carbonation of the concrete
- Inhibiting chloride penetration
- Control of moisture content – in order to slow the rate of corrosion
- To increase the effective cover of rebar, in order to achieve specified durability requirements (note that this cannot be used to reduce reinforcement cover in the initial design)
- Protection from sulphate attack or other deleterious chemicals (Beckett *et al.*, 1987)

5.5 SELECTION OF SURFACE TREATMENTS

Once the reasons for applying a surface treatment has been established, a set of required properties can be defined. This, together with environmental conditions as well as site restraints, will inform the selection of the treatment system. A product can then be selected and thus methods can be established which will inform the construction documentation. This basic process is shown in Figure 14 below. This process may require some iteration, as site conditions, environmental limitations of some products or costs restraints may limit the material or application method selection.

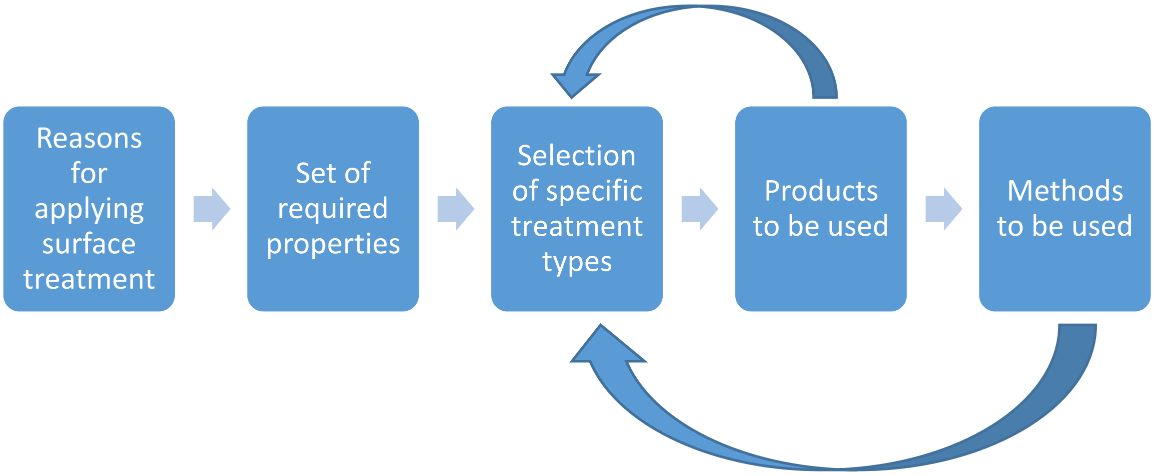


Figure 14: Basic Process for Selecting Surface Treatment System

It is very advantageous for engineers, clients and contractors to have detailed knowledge and experience in this regard. This will allow unsuitable systems to be disregarded at an early stage. However, with sufficient background information and understanding, and by focusing on critical factors one can define suitable generic product types and discuss these options with suppliers. Thus, a good selection can still be made. Inevitably some judgement is required and compromise is expected (Beckett *et al.*, 1987; Leeming *et al.*, 1997).

The following flow chart, provided by CIRIA Technical Committee 50 (Leeming *et al.*, 1997) gives a more detailed outline of this process:

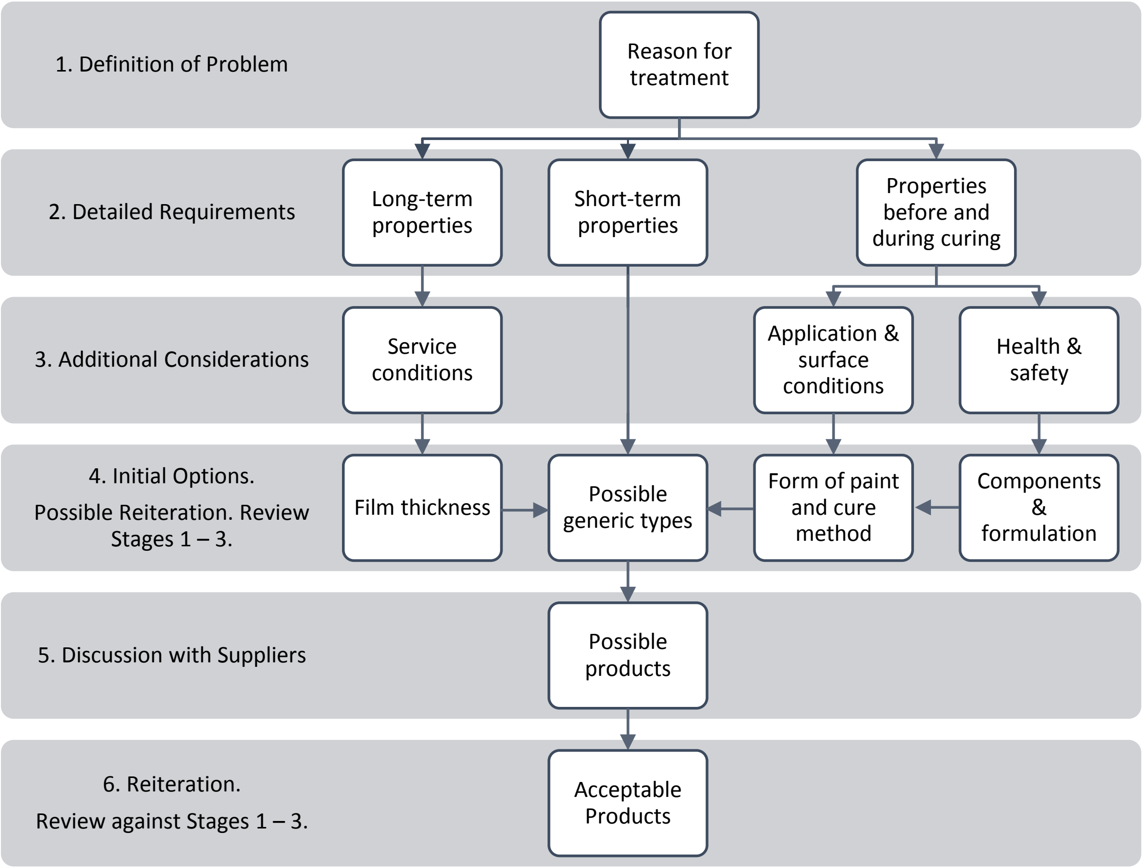
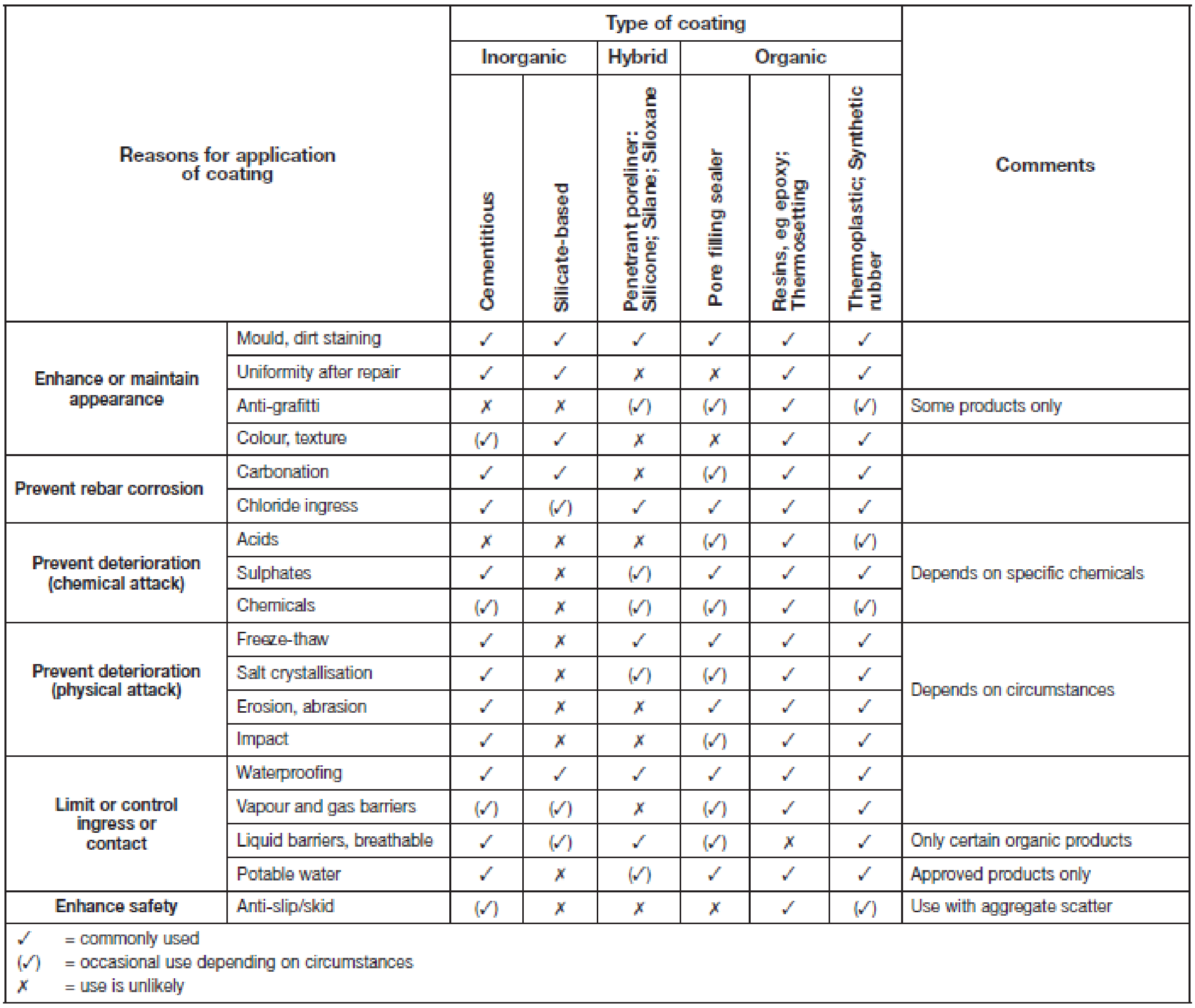


Figure 15: Detailed Process for Selection of Surface Treatments [redrawn from Leeming et al. (1997)]

In practice, however, the process of selecting and applying a surface treatment is much more complex due to the following (Leeming *et al.*, 1997):

- Suppliers typically provide technical data sheets which outline uses of and other technical requirements. However, environmental conditions, site and cost constraints, can vary significantly from one project to the other, making the standard requirements difficult to apply to the specific project.
- Often a range of different properties are required (such as carbonation barrier which allows transmission of vapour and ease of cleaning and slip resistance)
- Different suppliers may supply similar products meeting the specification criteria, but have different levels of performance.
- Varying extremes of environmental conditions may be in effect.
- Incorrect or inadequate specification provided, particularly with respect to site conditions.
- A variety of tests are available but there are no standard performance criteria.
- There is insufficient information available on in-service performance of specific treatments.
- Health and safety requirements may limit the choice of system.

A summary of common applications and the main types of coatings are given in Figure 16 below.



Reasons for application of coating		Type of coating						Comments
		Inorganic		Hybrid	Organic			
		Cementitious	Silicate-based	Penetrant poreliner: Silicone; Silane; Siloxane	Pore filling sealer	Resins, eg epoxy; Thermosetting	Thermoplastic; Synthetic rubber	
Enhance or maintain appearance	Mould, dirt staining	✓	✓	✓	✓	✓	✓	
	Uniformity after repair	✓	✓	✗	✗	✓	✓	
	Anti-grafitti	✗	✗	(✓)	(✓)	✓	(✓)	Some products only
	Colour, texture	(✓)	✓	✗	✗	✓	✓	
Prevent rebar corrosion	Carbonation	✓	✓	✗	(✓)	✓	✓	
	Chloride ingress	✓	(✓)	✓	✓	✓	✓	
Prevent deterioration (chemical attack)	Acids	✗	✗	✗	(✓)	✓	(✓)	Depends on specific chemicals
	Sulphates	✓	✗	(✓)	✓	✓	✓	
	Chemicals	(✓)	✗	(✓)	(✓)	✓	(✓)	
Prevent deterioration (physical attack)	Freeze-thaw	✓	✗	✓	✓	✓	✓	Depends on circumstances
	Salt crystallisation	✓	✗	(✓)	(✓)	✓	✓	
	Erosion, abrasion	✓	✗	✗	✓	✓	✓	
	Impact	✓	✗	✗	(✓)	✓	✓	
Limit or control ingress or contact	Waterproofing	✓	✓	✓	✓	✓	✓	
	Vapour and gas barriers	(✓)	(✓)	✗	(✓)	✓	✓	
	Liquid barriers, breathable	✓	(✓)	✓	(✓)	✗	✓	Only certain organic products
	Potable water	✓	✗	(✓)	✓	✓	✓	Approved products only
Enhance safety	Anti-slip/skid	(✓)	✗	✗	✗	✓	(✓)	Use with aggregate scatter

✓ = commonly used
(✓) = occasional use depending on circumstances
✗ = use is unlikely

Figure 16: Summary of common applications and the main types of coatings (Leeming et al., 1997)

It should be noted here that this table was originally published in 1997 by The Concrete Society (Leeming *et al.*, 1997) and was later reproduced in the ACI Concrete Repair Manual and was also used by Beushausen and Alexander (2011) in Fulton's Concrete Technology. The table has remained unchanged for 20 years since its original publication. Although somewhat outdated, it is still a good reference to be used even if it was only intended as an initial guide only. This may be an area for further research.

5.6 PERFORMANCE REQUIREMENTS OF SURFACE TREATMENTS

For the most suitable product to be selected, the performance against the relevant properties needs to be established with appropriate testing. In particular, it needs to be proven that the most important properties required from the system can be achieved to the required degree with the selected product(s) and methods. For example; if resistance to carbon dioxide diffusion is the primary aim, then the permeability to carbon dioxide should be investigated by a test such as that of EN 1062-6. The six primary tests relating to durability of the concrete for coating materials and systems are covered by EN 1062, and are listed below (Leeming *et al.*, 1997):

- Ingress protection
- Moisture control
- Physical resistance / Surface improvement
- Resistance to chemicals
- Increasing resistivity
- Cathodic control

Additionally, the coating system needs to be able to perform adequately in the specific exposure environment, both during application and in-service. Thus, the coating itself may be needed to perform under various other conditions, such as application to wet concrete, bridging of cracks, varying or extreme temperatures, abrasion etc. The thickness of the coating may also be needed to be tested.

For this, a detailed list of performance characteristics for surface treatments is given in Table 1 of EN 1504-2. Tables 3 – 5 of the EN 1504-2 code also provides additional performance requirements for each of the three surface protection categories. An overview listing these tests is given below in Table 14.

Table 14: Performance Tests for Hydrophobic Impregnations, Impregnations and Coatings

Hydrophobic Impregnation	Impregnation	Coatings
Loss of mass after freeze-thaw salt stress	Abrasion resistance	Shrinkage
Depth of penetration	Water vapour permeability	Compressive strength
Water absorption and alkali resistance	Capillary absorption	Thermal expansion
Drying rate	Adhesion	Abrasion resistance
Chloride ion diffusion	Chemical resistance	Cross-cut test
	Impact resistance	CO_2 permeability
	Pull-off strength	Permeability to water
	Reaction to fire	Capillary absorption
	Skid resistance	Adhesion
	Depth of penetration	Chemical resistance
	Chloride ion diffusion	Thermal shock resistance
		Severe chemical resistance
		Crack bridging ability
		Impact resistance
		Pull-off strength
		Reaction to fire
		Skid resistance
		Weathering
		Antistatic behaviour
		Adhesion to wet concrete
		Chloride ion diffusion

5.7 APPLICATION GUIDELINES

Correct application is vital to the success of a surface treatment on concrete. Often, access cost can be a substantial cost of the project. It is therefore highly advisable to spend time in ensuring that the necessary application considerations have been adequately assessed and the reasonable time should be invested in ensuring the application is completed properly.

The supplier should provide the expected properties of the particular system or product. The supplier will also provide application guidelines and properties of the products in the 'fresh' state and the method and duration of curing required. The supplier and applicator then need to provide guidance based on the specific environmental conditions for the project. The 'fresh' product properties may typically include (Leeming *et al.*, 1997);

- Viscosity and tendency to run or sag on inclined surfaces
- Type of application and its suitability, i.e. via brush, roller or spray.
- Density
- Solids content – this provides a measure of the theoretical coverage
- Typical coverage achieved on various types of surface
- Typical or recommended wet and dry film thicknesses
- Pot life
- Curing time
- Minimum and maximum coating intervals
- Shelf-life

Test areas may be required on-site for more precise data and to therefore establish the suitability of a coating system in a particular environment. Temperature is a critical consideration on site and affects many of the above-mentioned properties, both during application and curing. It should also be considered that weather conditions may need to be within specific temperature (and wind) ranges for suitable application and may cause delays on-site – this should be allowed for in the contract documents. Sufficient time should also be allowed for, for curing and consideration should be given for additional curing time due to inclement weather conditions. The environment may also need to be controlled, where weather conditions are limiting.

It should be noted that often properties given by suppliers are related to specific test conditions (such as temperature of 20° or humidity of 50%), which may be very different from site conditions. This needs to be considered in the selection of the treatment system and application thereof.

In general, suppliers will provide guidelines for the application of each of their treatment systems. These recommended guidelines should be followed by the applicator.

6 HYDROPHOBIC IMPREGNATION / PORE LINING PENETRANTS

Pore lining penetrants are low viscosity fluids which penetrate several millimetres into the concrete surface. They are generally based on a hybrid organo-metallic or organo-silicon materials (see Figure 10 above). They can sometimes chemically bind with internal surface of the concrete. They have the ability to considerably alter the water penetration resistance into concrete, to between 85% and 95%, compared to untreated concrete. They can also reduce the ingress of some water-soluble ions such as chlorides. They are therefore used to improve concrete durability (normally on unrepaired concrete). Silanes, siloxanes and siliconates are typical examples of these types of materials (Beckett *et al.*, 1987; Leeming *et al.*, 1997; Bijen, 2003; ACI Committee 546, 2014b).

Silanes, siloxanes and siliconates form silicones (more specifically polysiloxanes) which form a very thin lining within the walls of the concrete micropores and capillaries. Silicones have organic side groups which are water repellent and are thus impart the hydrophobicity to the material. However, these types of materials do not completely close pores and capillaries, therefore under a hydrostatic pressure (greater than the hydrophobic action), liquids such as water can still penetrate. They are therefore susceptible to water ponding. The hydrophobic action is therefore limited to wetting and absorption by surface tension effects and not physical blocking. They also, therefore, allow the concrete to 'breathe' by allowing the passage of water vapour. Figure 17, shows how the hydrophobic treatment alters the concrete surface properties and achieves the water repellent property. The contact angle between the concrete surface and water is increased above 90 degrees such that capillary action cannot occur and water falls off the concrete surface instead(Beckett *et al.*, 1987; Leeming *et al.*, 1997; Bijen, 2003; ACI Committee 546, 2014a).

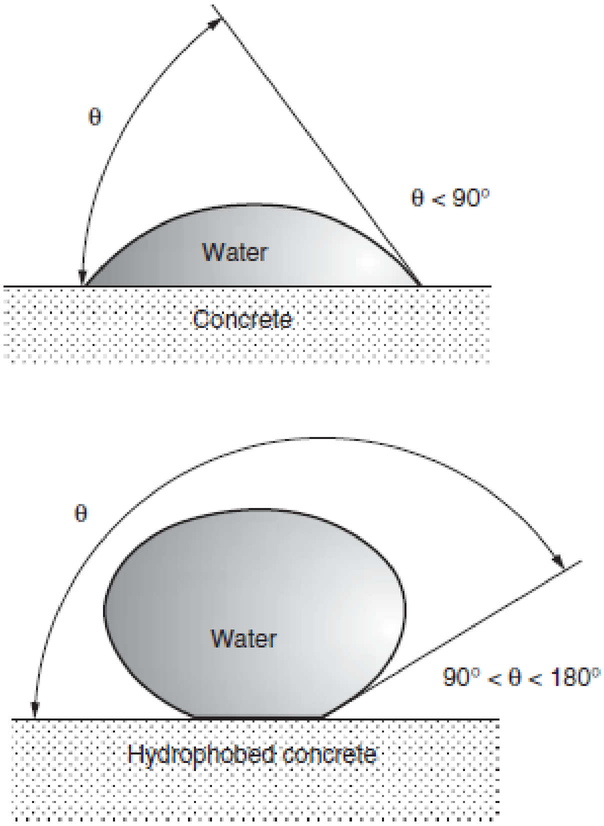


Figure 17: Effect of hydrophobic action at concrete surface (Bijen, 2003)

By the hydrophobic action, these materials can therefore limit the ingress of dissolved chlorides and other salts. However, they may still allow gaseous carbon dioxide to penetrate. They do not change the chemical resistance and abrasion resistance of the concrete (Beckett *et al.*, 1987; Leeming *et al.*, 1997).

Performance is sensitive to depth of penetration, which is dependent on the size of the penetrating sealer's molecules, the permeability of the concrete and moisture content. If good penetration is achieved, good weathering properties will be realised and they will not be affected by UV radiation. With low penetration (1 mm or less) the material will be vulnerable to weathering (Beckett *et al.*, 1987; ACI Committee 546, 2014a).

Pore liners do not have crack bridging abilities. However, the may line the inside of cracks and limit water ingress in existing cracks of small width. They will also not mask cracks or other defects (ACI Committee 546, 2014a, 2014b).

Pore lining penetrants are normally colourless and makes little changes to the appearance of the concrete (Beckett *et al.*, 1987; Leeming *et al.*, 1997; Thomas, 2002).

6.1 SILICONE-BASED PENETRANTS

6.1.1 SILICONE RESINS

Silicone resins have a high molecular weight and small molecular size. They are usually colourless, single pack products. They are composed of silicon and oxygen but have an organic group attached instead of a fourth oxygen group. They can be classified as 'hybrid' as they lie between purely inorganic and organic compounds (Thomas, 2002).

They generally require dry surfaces for application and can cure fairly quickly (as they cure by drying). Thus, the water-repellency they provide can be achieved very rapidly. Although their molecular size is relatively small, they are still large enough to limit penetration into much smaller pores – such as in good quality concrete. Care should therefore be taken in using these products on concrete with very high pore sizes as they may penetrate the concrete too deeply to be effective enough. Pre-treatment or repairs may therefore be necessary prior to application.

When used as an emulsion or solution in organic solvents methylsilicone resins dry to form tack-free coatings with good early water repellent properties. These coatings types of coatings were used on exterior masonry until the mid-1980's – their advantage being that once after evaporation the resin would impart good water repellent properties. However, they do change the appearance of the substrate as they remain on the surface. Therefore, a mixture of silanes, siloxanes and silicone resins are preferred for use (Thomas, 2002).

One major drawback is that if the application was not done correctly, limited penetration would result in premature degradation by weathering. With good penetration, however, up to 20 years of service life can be achieved.

6.1.2 SILANES

Silanes, as used in the construction industry, are in fact alkyl trialkoxysilanes and they come in several forms depending on their chemically bound side group, namely;

- Methoxysilane – Methanol side group
- Ethoxysilane – Ethanol side group
- Methylsialne – Methyl side group
- Butylsilane – long alkyl side chains with four carbon atoms
- Octylsilane – long alkyl side chains with eight carbon atoms

They can incorporate various levels of alcohol which can change its properties. An example is Methyltriethoxysilane, which at 78%, incorporates the highest alcohol content. This silane is used as binder in emulsion paints and cannot be used as a masonry water repellent. Iso-butyl-trialkoxy-silane and octyl-trialkoxy-silane have been reported to have good surface sealing properties (Thomas, 2002; ACI Committee 546, 2014b).

In general, silanes are transparent, have a low viscosity and are more moisture tolerant than silicones. Some of the advantages of using silanes are:

- Due to their low viscosity, they can achieve better and deeper penetration compared to siliconates and silicone resins.
- They have a high percentage of active materials of about 40% compared to silicone resins of 5 to 10% and siloxanes of 10 – 20% (Leeming *et al.*, 1997; Thomas, 2002; Bijen, 2003).

Their performance is however sensitive to the depth of penetration which in turn is dependent on the permeability of the concrete and the concrete moisture content (Beckett *et al.*, 1987).

Silanes need moisture to cure and are very volatile. They cure via a polymerisation reaction, forming polysiloxanes. They are typically used at high concentrations (at or above 40% silane content). Slow curing can be problematic and this can occur due to a very carbonated surface, very dry concrete, hot or windy conditions and this may cause the volatile silane to evaporate. Therefore, silanes may need to be used at very high concentrations of up to 100%. Due to health and environmental concerns over the evaporation of these volatile organic compounds some countries no longer consider silanes as an acceptable treatment material. To overcome this problem one can use a siloxane or silane-siloxane blend (Leeming *et al.*, 1997).

6.1.3 SILOXANES

Alkyl alkoxysiloxanes (Generally referred to as simply 'siloxanes' in the building industry) are slightly polymerised silanes. They were developed specifically to overcome the problem with the volatility of silanes. Generally, two types of siloxanes are available; oligomeric alkyl alkoxysiloxanes which are used for concrete, and polymeric alkyl alkoxysiloxanes which are further polymerised and have longer chain molecules. The latter is rarely used for concrete.

Siloxanes are transparent and are mobile and non-volatile. They are typically used at a concentration of 10 – 20%. They two main advantages they have over silanes are that they react faster and are less volatile i.e. they are less prone to evaporation loss. Siloxanes can therefore be diluted. They also therefore do not pose as high of an environmental risk as silanes.

6.1.4 SILICONATES

Siliconates are typically found as sodium and potassium methyl siliconate. They react with air-bound carbon dioxide to form potassium carbonate and polymethyl silicate on the walls of pores. The poly methyl silicates give them its water repellent properties. They have a very low alkali resistance and is therefore not recommended for new concrete or for concrete in general. The potassium carbonate production can lead to the formation of a white film over the surface or simply white deposits on the surface. This will be more pronounced with high volume applications on external surfaces. They can be washed out by rain. It is also therefore generally not encouraged to be used for external surfaces (Leeming *et al.*, 1997; Thomas, 2002).

Siliconates have, however, been used for in-plant impregnation of building materials made of clay, aerated concrete, and gypsum as well as chemical damp proof courses (Thomas, 2002).

6.2 OTHER TYPES OF PENETRANTS

6.2.1 STEARATES

These materials react with moisture to form a waxy water repellent film. They require dry surfaces to achieve good penetration. On alkaline surfaces they can achieve good performance for up to five years (Leeming *et al.*, 1997).

6.2.2 DRYING OILS

Drying oils such as linseed oil, soy bean oil and tung oil are mostly used for damp-proofing. Boiled linseed oil was widely used as concrete sealers or pore-liners in the past, but its use has declined with the availability of better performing materials. They are sometimes used as temporary sealers in new concrete or as a pre-coat to enhance the performance of other treatments. Drying oils can be turned into a soap by saponification and thus requires an acid wash pre-treatment on concrete surfaces. The performance of drying oils as a moisture barrier is inconsistent as they can achieve 20 – 30% water penetration reduction compared to 85 – 95% for most other (silicone based) pore liners. They are noted to be ineffective against chloride ion penetration (Lee*ming et al*., 1997; ACI Committee 546, 2014b).

6.3 DURABILITY STUDIES OF HYDROPHOBIC IMPREGNATIONS

Dai et al. (2010) studied the effectiveness of four types of silanes and two types of silicate based impregnations on extending the service life of concrete in marine environments, using a 1 year accelerated outdoor exposure test program. They also specifically studied the effect of cracks on these treatments. They concluded that;

- Silanes were highly efficient in reducing water absorption in uncracked concrete. Additionally, they found that a chloride barrier was built up that prevented chloride penetration. For long-term effectiveness they concluded that a 5 mm penetration depth was needed.
- For structures cracked prior to application they found that service-life can still be significantly extended using a silane as the efficiency of the treatment relied on penetration depth.
- Chloride penetration could not be totally prevented where cracks are formed after application, although the corrosion rate still reduced. They suggested that the service-life of the concrete would still be somewhat extended. They also further suggested that in this case, recoating would be needed.

Ibrahim et al. (1997) studied the effectiveness of the following surface treatment systems in reducing chloride-induced corrosion:

- Sodium silicate
- Silicon resin solution
- Silane/siloxane
- Alkyl alkoxy silane
- Silane/siloxane with acrylic top coat
- Two component cement-based acrylic coating

They found that the silicone resin and silane/siloxane blend markedly enhances the time to corrosion and cracking, but that the rate of corrosion was not much different to the uncoated concrete specimens. The silane/siloxane with a top coat was also effective in reducing reinforcement corrosion. It should also be noted here that the difference in effectiveness between a pure silane and a silane/siloxane blend in increasing the time to initiation of corrosion was shown to be over 600% better in the pure silane, measured by ASTM C876 criterion of 270mV SCE.

In their comprehensive investigation on research done on various surface treatments, Basheer et al. (1997) showed that;

- Silanes do not improve the resistance of concrete to carbonation
- Siloxanes with large alkyl groups may marginally reduce carbonation
- Two or more coats are preferable than a single coat

They did however find that the works by Pfeifer et al. suggested that silane may be able to reduce carbonation due to the concrete drying out thereby reducing the rate of carbonation. Basheer at el. therefore felt that these results were contradictory to common understanding and recommended this be tested where required.

In the same work, with regards to chloride penetration resistance, Basheer et al. found that silanes performed excellently. A two-coat silane primer with an acrylic top coat was also found to be highly effective. Siloxanes were reported to initially delay the onset of steady-state diffusion but ultimately fail to retard the diffusion of chlorides. A penetrating silane-siloxane treatment with 40% silane solution was found to be perform better.

Christodoulou et al. (2013) conducted long-term durability studies on eight silane treated RC bridge beams, 10 – 20 years after application. They found that even 20 years after application, the silane provided a residual hydrophobic effect. Although, the effect was much less than a newly treated area of the same structure, due to environmental-related degradation.

Wright et al. (1993) investigated the effectiveness of boiled linseed oil and mineral spirits on concrete pavements in inhibiting chloride ion intrusion and salt-water absorption. They conducted penetration, salt water absorption, vapour transmission, abrasion, chloride ion intrusion, surface scaling resistance, and rapid freeze-thaw tests. They found that linseed oil was the most effective sealer at reducing chloride ion intrusion and that they were comparable and more effective than both silane.

7 IMPREGNATION / PORE BLOCKING SEALERS

Pore blocking sealers or impregnators are low viscosity solutions that can penetrate 1 – 3 mm into concrete and effectively block pores. They differ from pore-liners or hydrophobic coatings in that passage of water and other vapour and gases are more restricted (Beckett *et al.*, 1987). Figure 11 (a) and (b) on page 33 shows a pictorial representation of this difference.

Pore blocking sealers can be divided into two broad categories, namely (Leeming *et al.*, 1997);

- Materials which react with and bond to concrete surfaces producing pore-sealing products. Examples of these are:
  - Silicates (sodium and potassium)
  - Silicofluorides (magnesium and zinc)
- Materials which in themselves form pore-sealing products, without reacting with the concrete.
  - Single-pack (non-reactive) acrylics and polyurethanes
  - Single-pack moisture curing polyurethanes
  - Two-pack (reactive) epoxies and polyurethanes

This type of surface treatment is often used as surface hardeners for floors and dust-proofing. They are also used for pre-treatment before a primary coating material is applied (Beckett *et al.*, 1987).

The use of each of these product types are discussed below.

7.1 SILICATES (NA, K)

7.1.1 BACKGROUND TO THE USE OF SILICATES

The use of this technology can be dated to the ancient Egyptians (4000BC) and has been found in the ruins of Pompei and Herculaneum (2000BC).

The first modern use of this type of technology was during the late 19th century in which a twin-pack paint system was developed by A. W. Keim. Consequently, many decorative facades across Northern Europe, constructed during the late 1900’s and after, were found to be in excellent condition due to this technology.

The first single-pack formulation was developed in 1960. These organic polymer dispersions allowed for more stable formulations and longer shelf life. This allowed silicate paints to compete with organic emulsion paints with the added benefits of its inorganic properties (Gatrell, 2002).

7.1.2 MATERIAL COMPOSITION OF SILICATES

Silicate paints are normally water-based and solvent free, although some products may contain very small amounts of solvent, up to about 0.5%. They contain naturally occurring raw materials and are environmentally friendly. They are currently being promoted as the ‘green solution’ to solvent based systems (Gatrell, 2002).

Silicates are based on four main components;

- The binder system
  - Inorganic binder – The inorganic binder is the main and larger component and is known as waterglass. It is a clear, colourless and highly alkaline liquid. This is the component that will migrate into mineral pores and, by silicification, will form a very strongly bonded, insoluble coating over the mineral substrate

    - Organic binder – This component is much smaller. It is added to stabilise the single-pack formulations. It will also assist in resisting moisture ingress in early service days and improve the coatings durability by improving adhesion and reducing chalking.
- The solvent or vehicle
    - Silicate paints are always water-borne
    - Some formulations may contain 0.5% or less coalescing solvent. However, these coatings are still considered to be solvent-free
- Fillers and Pigments
    - Naturally occurring mineral fillers such as calcite and quartz are used. These prevent in-can reactions with the silicate
    - Inorganic pigments are typically used. These pigments reduce the risk of colour fading
- Additives
    - Numerous additives may be used by manufacturers. These additives perform a range of different functions, from increasing shelf-life to enhancing specific properties such as viscosity, sag resistance and water repellency

7.1.3 PROPERTIES OF SILICATE SURFACE TREATMENT SYSTEMS

Soluble sodium silicates have been used for many functions in the concrete industry, such as in the cement clinker production and concreting accelerators. They are mainly used for floor hardening and dust-proofing of concrete floors. Whilst they have been used for a long time, there appears to be relatively very little research available (compared to silanes and siloxanes) on their properties when used as concrete surface sealers, particularly with respect to its potential to improve concrete durability by improving chloride and carbonation resistance (Beckett *et al.*, 1987; Leeming *et al.*, 1997; Thompson *et al.*, 1997; Dai *et al.*, 2010; Baltazar *et al.*, 2014).

It is claimed that silicate surface sealants can decrease permeability, increase hardness and improve overall durability of concrete (Beckett *et al.*, 1987). However, a limited amount of research is available. The following properties have been reported:

- The mechanism of protection is not fully understood. There are three possible mechanisms mentioned in literature, and this may differ from product to product:
    - SiO_2 precipitating into pores, effectively sealing them
    - Silicates reacting with excess calcium to for Calcium-Silicate-Hydrates
    - Silicates forming as expansive gel similar to alkali silicate reaction products and filling concrete pores by swelling (Thompson *et al.*, 1997)
- There are conflicting reports concerning the ability of silicate-based sealers to improve the water permeability properties of concrete;
    - In studying the properties of sodium silicate sealers Thompson et al. used the National Cooperative Highway Research Program (NCHRP) Report No. 244 test method and together with tests done by others and his research (he actually specifically investigated chloride penetration, and noted that this test method is highly complex) concluded that they were moderately effective as surface sealers (Thompson *et al.*, 1997). The NCHRP 244 test method considers sealers giving a minimum of 75% reduction in absorption as a criterion.
    - Also using the NCHRP 244 test method, with a reduced pass requirement of 65% absorption to account for the lower temperatures used in this research, Mirza et al. found that silicate sealers were not adequate in reducing water absorption at

  - low temperatures. The silicate they investigated gave a 10 – 15% water absorption reduction (Mirza, Abesque and Bérubé, 2011).
  - Baltazar et al. studied commercially available silicate impregnations and concluded that they were effective in improving the water permeability performance of concrete. They further commented that higher concrete moisture contents improved the efficacy of the treatment on more porous concrete. They suggest that this is due to moisture limiting the depth of penetration in more porous concrete, providing a more impermeable surface layer (Baltazar *et al.*, 2014).
  - Leeming et al.'s technical report on surface treatments systems states that sodium and potassium silicates do not prevent water penetration but may reduce the rate of penetration. They further report that these silicates are ineffective when used on poor quality concrete and carbonated concrete (Leeming *et al.*, 1997).
- Abrasion resistance is improved. Although higher moisture contents reduced the effectiveness of the surface sealer (Baltazar *et al.*, 2014).
- Chemical attack is not prevented, but the rate may be reduced (Leeming *et al.*, 1997).
- Sulphate attack is not prevented and there is no beneficial effect compared to untreated concrete (Ibrahim *et al.*, 1999).
- They are ineffective against chloride ingress (Leeming *et al.*, 1997; Thompson *et al.*, 1997). Ibrahim et al. (Ibrahim *et al.*, 1997) reported a very small beneficial effect compared to untreated concrete. They reported that silicate sealers were by far the least effective in reducing chloride ingress compared to silicone resins, silanes, silane/siloxane blends, acrylic coatings and a silane/siloxane blends with acrylic top coats.
- The corrosion rate of concrete is unaffected by a sodium silicate surface treatment and performs similar to untreated concrete (Ibrahim *et al.*, 1997, 1999).

Notwithstanding the above findings, some literature does appear to suggest that the use of silicates can be used to improve durability of concrete. Pigino et al. (2012) studied an ethyl silicate and found promising results. They reported that ethyl silicates "greatly limits the concrete's water sorptivity, with considerable advantage in terms of expected concrete durability". They also report that the same formation provides a substantial reduction in chloride penetration and carbonation. However, it is uncertain whether this formation can be compared to the above-mentioned silicate sealants (typically sodium and potassium). At one point, they appear to indicate that this ethyl silicate (specifically named as tetraethyl-orthosilicate) is in fact an alkoxysilane.

In the comprehensive Handbook of Coatings for Concrete, Gatrell (2002) reports that silicates enhance the hydrophobic nature of concrete, whilst allowing the concrete to breathe. Gatrell also presents the following properties of silicate sealers, as mentioned below;

- They protect against solar radiation
- They help to reduce thermal movement caused by temperature fluctuations
- They are incombustible and exhibit a low smoke toxicity
- Being essentially inorganic in nature, they discourage the growth of fungus and algae
- They can be used to resist chemical attack (such as for acid rain, air pollution and vehicular exhaust fumes).
- They are low cost
- They can be applied in a short period of time with minimal disruptions and no fumes or odours released
- They are low maintenance and provides a durable finish for many years.

7.2 OTHER TYPES OF IMPREGNATORS OR SEALERS

For a treatment to effectively block pores a sufficient amount of solids need to be carried into the concrete. Thus, a balance needs to be found between the concrete porosity and the number of applications. There are a number of proprietary solvented products which are based on thermoplastics and thermosetting resins that achieve a good balance, namely;

- Single-pack (non-reactive) acrylics and polyurethanes
- Single-pack moisture curing polyurethanes
- Two-pack (reactive) epoxies and polyurethanes

Two or three coats are typical with average quality concrete, but site trials may be necessary. Where high amounts of materials are required, solid contents can be increased with the allowance for less deep impregnation.

These surface protection systems may not provide good resistance to chemical attack – surface coatings should be considered.

Compared to surface coatings, these systems typically require less surface preparation, as adhesion is not a requirement – as they function by impregnation. For this reason, some pore-sealers are used as primers before coating friable surfaces. A dry surface is generally required for application in order to achieve the necessary penetration. Surfaces do need to be free of mould oils and curing membranes (Leeming *et al.*, 1997).

8 SURFACE COATINGS

Surface coatings are treatments that form a continuous protective layer on the surface of the concrete. These treatments are typically 0.1 mm – 5 mm thick, but may be greater than 5 mm for certain applications (Beckett *et al.*, 1987; BS EN 1504-2, 2004).

Traditionally some form of levelling or fairing coat may be required prior to application of a coating as concrete surfaces can often have partial small voids (blow-holes) or may have a varying profile or some weak or friable concrete areas. This is necessary to eliminate weak spots in the film. Opening up of voids and removal of weak concrete areas may be required and can be achieved with grit-blasting or other similar techniques (Leeming *et al.*, 1997).

These types of coatings are the most common surface protection system used, as evidenced by Tilly and Jacobs (2007) (referred to as barrier systems). Several types of surface coatings are available, and is mainly divided into organic and inorganic type coatings. A brief discussion of the various types is given in 8.1 to 8.2 below, with detailed discussions on Polymer-Modified Cementitious Coatings and Polyurethanes given in sections 8.3 and 8.4.

8.1 INORGANIC COATINGS

SILICATE-BASED COATINGS

Sodium and potassium silicates containing fillers and pigments may be used to form protective coatings. These coatings have been used for many years on facades in Germany. See section 7.1 for more information on the use of these types of materials (Leeming *et al.*, 1997).

POLYMER-MODIFIED CEMENTITIOUS COATINGS

Polymer-modified cementitious coatings are probably the most widely used surface coatings. A detailed discussion on this technology can be found in section 8.4.

WATER-BORNE EPOXIES

Epoxy resin technology has been available since the 1960's (Leeming *et al.*, 1997) and has been used for (Beinborn and Darwen, 2002):

- Surface coatings
- Self-levelling floors and screeds
- Crack injection products
- Patch repair systems
- Bonding agents, bedding mortars and bolt anchoring

Epoxy systems are considered to give high performance and structural longevity, but also traditionally comes at a higher price than their single-component thermoplastics and synthetic rubber counterparts (Leeming *et al.*, 1997; Beinborn and Darwen, 2002).

Typically, low molecular weight epoxy systems are used in solvent-free systems for concrete – known chemically as bis-A epoxy resins, with a molecular weight of about 380. Higher molecular weight systems (>760) are used for more advanced systems, conventionally used in heavy duty applications and coatings for structural steel in marine environments. Other commonly used epoxies are based on alkyl glycidyl and hexanediol diglycidyl ethers. The most commonly used epoxy in civil engineering application is a mixed bisphenol-A/bisphenol-F epoxy resin modified with alkyl glycidyl ether (Beinborn and Darwen, 2002).

One of the main problems with epoxy resins is controlling the effects of water and carbon dioxide during curing. Water and carbon dioxide can react in the epoxy leading to the formation of carbonic acid which manifests as surface defects in the film and can lead to poor adhesion and lower than expected mechanical strength and chemical resistance. For this reason, the selection of curing agent is very important – and should be specified the supplier.

A wide variety of properties can be achieved with epoxy resin systems. Low viscosity solvent-free systems are available and are commonplace as are water-based systems. Flexible systems are available and with continuous advances in this technology, the common problem of adhesion need not be an issue any longer in modern epoxy systems.

Epoxy systems can be used to address the following challenging conditions (Leeming *et al.*, 1997):

- "Further enhancement of physical and barrier properties, adhesion, chemical resistance and anti-corrosion characteristics
- The ability to form thixotropic, non-sag coatings on vertical surfaces (including spray applications)
- The capability of being applied to fresh concrete, in addition to more mature but damp surfaces
- The provision of a temporary moisture barrier which allows the application of impervious coatings with a minimum delay, e.g. over-coating with solvent-free or low solvent products may be carried out after less than 24 hours and tolerance to wind during curing as well as rain (after only six hours)."

Refer to specialist literature for more detailed information.

8.2 ORGANIC COATINGS

THERMOPLASTICS AND SYNTHETIC RUBBERS

These coatings are typically single-pack, ready-to-use products. They are made of polymers either dissolved in an organic solvent or dispersed in water and the film forming action is by physical drying – thus very slow or fast drying can be detrimental to the integrity of the coating. These coatings therefore require careful consideration of ambient temperature and wind speed, absorptivity of the concrete substrate and time between successive coats. Internal use also needs careful thought and may need ventilation or extraction. These coatings are normally used for decorative masonry coatings and protective treatments for masonry and exposed concrete.

Typical formulations are based on polymers such as:

- (Meth)acrylics
- Styrene-acrylics
- Styrene-butadiene
- Vinyl acrylics (vinyl chloride-vinylidene chloride acrylics)
- Vinyl acetate-ethylene-vinyl chloride

They are available as pigmented systems, in a wide range of colours, and some are also available as non-pigmented clear systems.

A common problem with assessing and reporting on the performance of these coatings is that often the exact polymer composition is not known – which is partly due to the vast number of different formulations available – and very general terms such 'acrylic' or 'vinyl' are used. However, in general these coatings can provide the following properties (Leeming *et al.*, 1997):

- Good weathering and water ingress resistance
- Good sulphate ion and chloride ion resistance
- Excellent carbon dioxide barrier properties
- Crack-bridging abilities over existing cracks even at low temperatures
- Relatively low resistance to water vapour transmission
- Minimal long-term dirt pick-up
- Good adhesion
- Ease of use

Even better performance can be achieved by using a dual system, such as a low viscosity silane-siloxane/acrylic surface primer with a methacrylate top coat.

These coatings may have some problems when permanently submerged, such as the formation of fine cracks due to the extraction of plasticizer, softening of the coating, loss of adhesion or inadequate resistance to water under hydrostatic pressure. However, chlorinated rubbers are an exception – they have been used successfully for many years for coating swimming pools and protecting steel in polluted industrial environments. They possess good adhesion under submerged conditions, have good carbon dioxide resistance, good abrasion resistance as well as some flexibility. They are, however, sensitive to UV exposure.

THERMOSETTING POLYMERS

The most common thermosetting coatings are based on epoxy and polyurethane resins. They can be formulated to be penetrating sealers and high-build coatings.

In general, the following properties can be expected (Leeming *et al.*, 1997):

Advantages	Disadvantages
• Excellent adhesion, even to wet surfaces • Very low curing shrinkage • High chemical resistance – to acids, alkalis and some solvents • Excellent resistance to water, salt and gases • Good durability • Variety – products can be tailored to specific application and service needs	• Intolerant to poor surface preparation or contamination • Short pot-life at high temperatures • Slow curing, particularly below 15°C, no curing should be expected at 0-5°C • The possibility of water entrapment due to its high water resistance • Lack of flexibility in some formulations • Lack of colour stability and rapid chalking (although this may not necessarily hinder performance) • Poor adhesion between old and new coatings • Experienced / skilled applicators are desirable • Relatively high cost compared to many single-pack coatings

Other types of organic coatings, not discussed in this work are:

- Alkyds and Drying Oils
- Bituminous Coatings

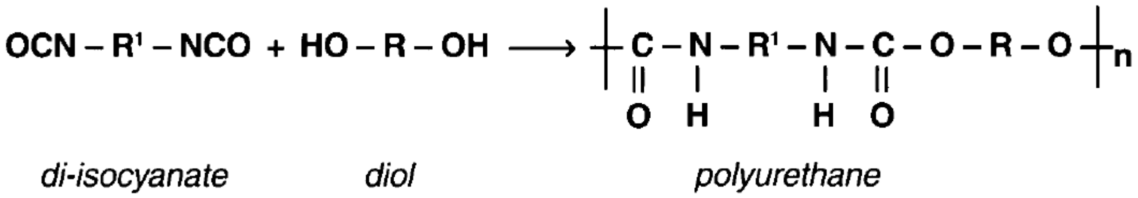
8.3 POLYURETHANES

Polyurethanes, a type of polymer, are manufactured in a wide variety of forms and have a very wide range of applications from foams for insulation, elastomers used in automotive parts, shoes and tyres, noise control, fibre composites, adhesives as well as paints and coatings (Wilson, 2002; Engels *et al.*, 2013). They are used as clear coatings for glass, coatings for floors, roof coatings and anti-corrosive top coat paints (Howarth, 2003). They are also used for surface coatings for concrete protection (Wilson, 2002).

8.3.1 CHEMICAL COMPOSITION

Considering the wide variety of polyurethanes on the market, it would be necessary to breakdown polyurethanes into the various chemical compositions available, in order to understand the various possible uses and properties. This is discussed in the sections below, as given by Wilson (2002). It should, however, be kept in mind that it is difficult to generalise the properties of the many forms of polyurethanes. As such, the sections that follow should be used only as a guide.

A basic polyurethane is produced by the reaction of di/poly-isocyanate and a di/polyol as shown in Figure 18 below, with the di-isocyanate being the most important building block of the polyurethane. A catalyst is also generally required to allow the reaction to occur at a sufficiently rapid rate and at lower temperatures (Wilson, 2002; Chattopadhyay and Raju, 2007).



$$\mathrm{OCN-R^1-NCO} + \mathrm{HO-R-OH} \longrightarrow \left[\underset{\mathrm{O}}{\underset{\|}{\mathrm{C}}} - \underset{\mathrm{H}}{\underset{|}{\mathrm{N}}} - \mathrm{R^1} - \underset{\mathrm{H}}{\underset{|}{\mathrm{N}}} - \underset{\mathrm{O}}{\underset{\|}{\mathrm{C}}} - \mathrm{O-R-O} \right]_n$$

Figure 18: Basic reaction to form a polyurethane (Wilson, 2002)

8.3.1.1 Prepolymer (Di-isocyanate)

Di-isocyanates are available commercially as either aromatic and aliphatic. These are the two main types, with cycloaliphatic and polycyclic in structure types also available. The most common of which are shown below.

1. Aromatic
    a. Methylene diphenyl di-isocyanate (MDI)
    b. Toluene di-isocyanate (TDI)
2. Aliphatic
    a. Hexamethylene di-isocyanate (HDI)
    b. Isophorone di-isocyanate (IPDI)
    c. Meta tetramethyl-xylene di-isocyanate (m-TMXDI)

Aromatic isocyanates are more reactive than the aliphatic or cycloaliphatic di-isocyanates. Different properties are given to the polyurethane depending on the type of prepolymer used. Aromatic di-isocyanates produce more rigid polyurethanes than the aliphatic type but have weaker oxidative and ultraviolet properties. Generalised properties of aromatic versus aliphatic type isocyanates are given in Table 15 below (Wilson, 2002; Chattopadhyay and Raju, 2007):

Table 15: Generalised properties of isocyanate polyurethanes (Wilson, 2002)

	Chemical Resistance	**Weathering Resistance**	**Flexibility**	**Hardness**	**Abrasion Resistance**	**Heat Resistance**	**Water Resistance**
Aliphatic	Good	Excellent	Good	Good	Good	Good	Very Good
Aromatic	Excellent	Poor*	Fair	Excellent	Excellent	Very Good	Excellent
*Aromatic isocyanates significantly discolour in exposure to UV light							

Most of the above isocyanate monomers are considered toxic and requires the addition of prepolymers, adducts, trimers and dimers, which increases their molecular weight thereby reducing its toxicity. Some of these molecules adds to the properties of the polyurethane, such as hardness.

8.3.1.2 Polyols / Co-reactants

Polyols are available in various forms and functions. Thus, the choice of polyol plays an important part in the polyurethanes performance. The four most common types and their properties are given below.

Table 16: The effects of polyols on the properties of polyurethanes (Wilson, 2002)

	Chemical Resistance	**Weathering Resistance**	**Flexibility**	**Hardness**	**Abrasion Resistance**	**Heat Resistance**	**Water Resistance**
Polyester	Fair	Good	Excellent	Fair	Good	Poor	Good
Polyether	Fair	Fair	Excellent	Poor	Poor	Poor	Fair
Polycarbonate	Fair	Good	Excellent	Fair	Good	Fair	Good
Polyacrylate	Good	Excellent	Good	Good	Good	Good	Good

The choice of the polyol system will depend on the application requirements.

Whilst the above information is particularly important to the manufacturer to correctly formulate the polyurethane system, it would also be useful for engineers, contractors and end users to make a more informed choice of coating system.

8.3.2 FORMULATIONS

Several common systems are available as discussed below, some important features of each system are listed.

8.3.2.1 Two-component polyol / poly isocyanate

- These are the most common type of polyurethanes on the market
- The polyol blend and poly-isocyanate prepolymer is kept separate, often already in the correct mix ratio. Thorough mixing and stirring is required. Once the reaction is initiated, viscosity will continue to increase. They therefore have a limited pot life.
- The poly-isocyanate prepolymer can react with air-borne moisture, to form a polyurethane and carbon dioxide. This can occur if the components are not pre-dried and is thus a risk, particularly in humid conditions. Temperature will also influence this reaction. As the viscosity increases, it becomes more difficult for the polyol components to react with the prepolymer, increasing the above-mentioned effect. Such a scenario may lead to variance in performance and appearance of the polyurethane and, in severe cases, may result in bubbles and pinholes due to carbon dioxide gas release.

8.3.2.2 Moisture-cured single-component

- These polyurethanes can be produced by the reaction with water alone. Such systems are typically single-pack solutions.
- This is much harder to manufacture, as all the additives need to be pre-dried to avoid the reaction with water in the tin. Once the tin is opened the reaction will start, and can be immediately applied to the concrete surface.
- Moisture cured system can be formulated to produce a range of properties. However, there are a few limitations;
    - They are very sensitive to atmospheric humidity and should only be applied in a limited humidity range. The curing will affect the quality of the coating. The effect of humidity on curing is given in Table 17 below.
        - If the humidity is too high, there will not be sufficient time for the carbon dioxide to be released, and it will become trapped in the coating film. If the humidity is too low, the curing will become too slow. Thus, finding the right time for application may be difficult.
    - The maximum film thickness applied should be ±100 – 200microns. If the film thickness is too high, carbon dioxide gas may become stuck behind the film. This will lead to an insufficient bond to the substrate and ultimately decreased performance and durability.

Table 17: Quality of curing with humidity for moisture-cured polyurethanes (Wilson, 2002)

Relative Humidity (%)	Curing Quality
0 – 20	Very little
20 – 30	Very slow
30 – 45	Slow
45 – 80	Good
80 – 90	Slight gassing
90 – 100	Severe gassing

8.3.2.3 Moisture-triggered, latent hardener

- These are also single-pack systems. However, by including a latent hardener, the humidity and film thickness limitations can be overcome.
- In these formulations, the latent hardener reacts with atmospheric moisture, the activated hardener that is produced then reacts with the prepolymer to form the polyurethane.
- This is generally achieved by the addition of an oxazolidine hardener, of which many different types are available. Refer to Wilson (2002) for more information. The reaction of oxazolidine with water is much faster than that of a prepolymer and thus inhibits the effect of this unwanted reaction.
- Thus, atmospheric humidity is of much less significance as well as the risk of carbon dioxide bubbling. Table 18 shows the curing ability of these systems with humidity.
- The atmospheric humidity will still, however, affect the rate of cure. The influence will be markedly less important than normal moisture-cured system. Moisture-triggered systems also have no upper limit of humidity and can even cure under water.
- Oxazolidines have a low viscosity and can significantly reduce the VOC (volatile organic compounds) content. It is thus common to use aliphatic isocyanates (IPDI and m-TMXDI) with oxazolidine. Aromatic systems are not suitable with oxazolidines. All moisture-triggered systems available are thus aliphatic in nature and can be used for external purposes (provided they are formulated correctly).

Table 18: Quality of curing with humidity for moisture-triggered polyurethanes (Wilson, 2002)

Relative Humidity (%)	Curing Quality
0 – 10	Little
10 – 20	Slow
20 – 30	Medium
30 – 100	Excellent

8.3.2.4 Two-component Polyurea systems

- These two component systems are used for very specialised applications.
- In these system, the poly-isocyanate reacts with a polyamine instead of a polyol. This reaction occurs very fast and thus pre-mixing is not possible and only two-pack solutions are available.
- They cure extremely fast. Using TMXDI, which is the slowest curing isocyanate, these coatings can cure in 20 seconds, when sprayed over a block of ice.
- Due to the fast curing, specialised spray equipment is required.
- They are used in severely cold conditions where their rapid curing is an advantage (Bassi and Roy, 2002; Howarth, 2003).

8.3.2.5 Water-based single-pack systems

- Water-based polyurethanes have attracted an increased interest largely due to its relatively low VOC content.
- These are polyurethane dispersion systems (PUD's), which is produced in a similar manner to other water based dispersion or emulsion systems.
- The vast majority of PUD's are aliphatic in nature. However aromatic PUD's are also available.

- They are being used as an alternative to the above-mentioned solvented systems for its environmental and health and safety advantages. Also, the ease of using water only for clean-up is making them more attractive.
- Due to them being water-based systems, there are severe limitations on their external use. Severe cold conditions will prevent the use of these systems. However, in the right conditions they can achieve excellent properties.
- They have a small market-share at present, as other water-borne emulsion system tends to be cheaper (Wilson, 2002; Chattopadhyay and Raju, 2007).

8.3.2.6 Water-based two-component systems

- These are relatively newly developed systems.
- They have a limited pot-life and some reaction between the isocyanate and water may occur leading to bubbling, especially if applied coating thicknesses are too thick.
- Whilst they are currently not commonly in use, their importance is likely to grow in future.
- Like the PUD'S, they will likely have more use in internal settings due to their sensitivity to inclement weather conditions.

8.3.2.7 Fluorinated system

- Similar to many other fluorinated systems, fluorinated polyurethanes are characterised by an extremely high level of durability and are used where extreme levels of performance are required.
- They can uniquely simultaneously possess a low surface energy, with low friction, good dirt repellent, biological inertness, good resistance to corrosive agents, low ion and water permeability, high flame resistance, UV radiation resistance.
- They are available in a wide range of mechanical properties.
- They can be formulated into many forms such as single-pack or twin-pack etc.
- They are extremely expensive and will only be used in niche markets (Wilson, 2002; Chattopadhyay and Raju, 2007).

8.3.3 LATEST RESEARCH

A summary of research into the use of polyurethanes for improving the durability of concrete is discussed below.

Swamy and Tanika (1993) investigated four different surface coatings (an acrylic rubber, a polyurethane rubber, a polybutadiene rubber and an epoxy resin) for its ability to control chloride penetration, the long-term stability of the coatings (weathering and UV resistance) and its crack-bridging ability over 5 years.

- They found the polyurethane and polybutadiene pre-cracked specimens to have inadequate ultra-violet light radiation exposure resistance, both showing extensive cracking for crack widths of 0.1 mm to 3.0 mm. The Polyurethane performed somewhat better in normal weathering exposure (independent of UV exposure) but did fail for pre-cracking of 3.0 mm. The acrylic coating was found to have performed very well, showing no visible changes in the coating after 5 years of exposure.
- All three rubbers performed well in the accelerated sea spray tests, showing no blistering or cracking. The polybutadiene, however, did show some discolouration. All four coatings were also very effective in preventing chloride penetration.
- All coatings maintained good adhesion to the concrete specimen surfaces.

- The polyurethane showed no deterioration in the accelerated chloride penetration test performed (100 dry-wet cycles and salt spray test) although it had a lower adhesion compared to acrylic rubber, polybutadiene rubber and epoxy resin. However, the authors did not report the adhesion prior to chloride tests and is therefore difficult to assess the relative change in adhesion. The authors did however, report that adhesion had not deteriorated sufficiently to impair the adhesion.
- All four coatings, including the polyurethane rubber, were extremely effective in chloride penetration prevention. They were also all effective in preventing rebar corrosion.
- Authors concluded that the polyurethane coatings were good in chloride penetration prevention and rebar corrosion with good adhesion properties. However, it has poor resistance to oxidation, sunshine and rain and likely to fail under continuous exposure to natural environments.

Buenfeld and Zhang (1998) measured chloride diffusion rates of various concrete coatings and sealers and found that the polyurethane sealer (aliphatic isocyanates with aliphatic and aromatic hydrocarbons solvent) had the lowest diffusion coefficient compared to the silane, polymer modified cementitious coating (two-component acrylic-modified) and the acrylic sealer (solvent based methacrylate) tested. The acrylic and polyurethane coatings used were too resistant to obtain any results after one year of testing.

A summary of their diffusion results is shown graphically below.

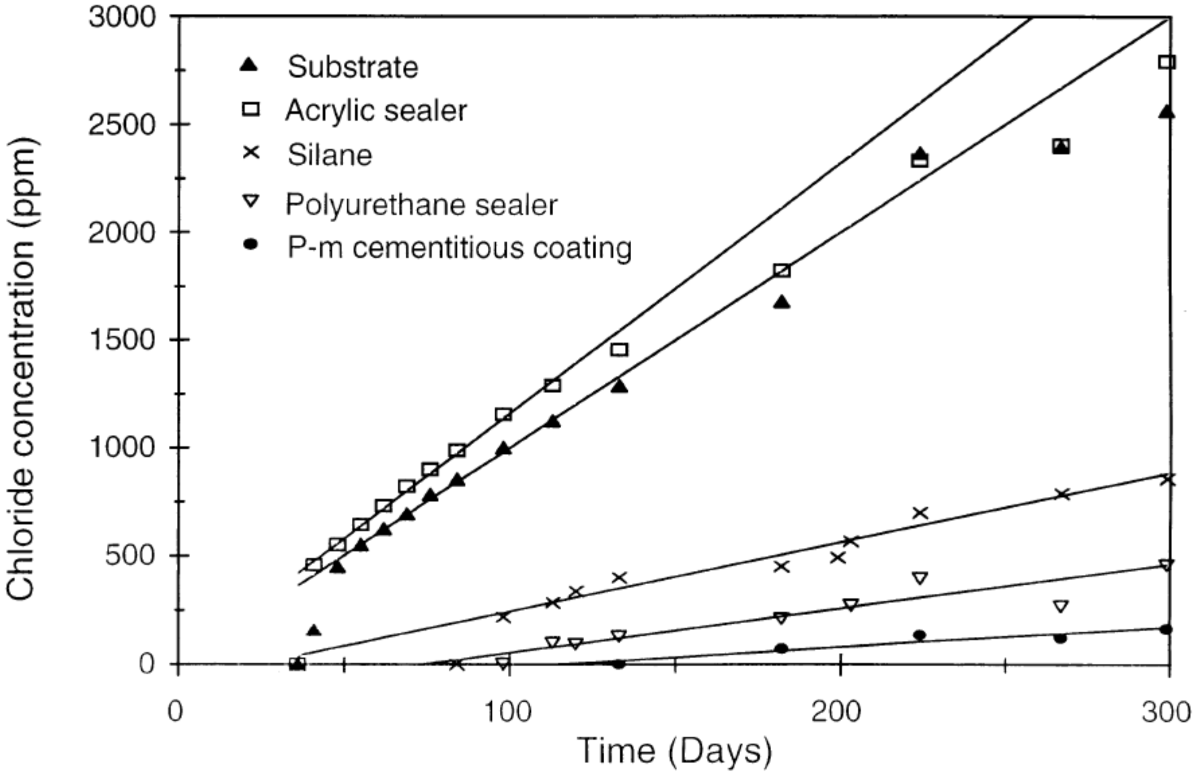


Figure 19: Average diffusion cell results of control and treated specimens by Buenfeld and Zhang (1998)

Almusallam et al. (2003) compared 2 types of each of the following coatings: Acrylic, polymer emulsion, epoxy, polyurethane, chlorinated rubber.

- The chloride permeability of the polyurethane coatings, as measured by ASTM C 1202, was found to be one-tenth of uncoated concrete, and was also found to have the lowest chloride diffusion coefficient.

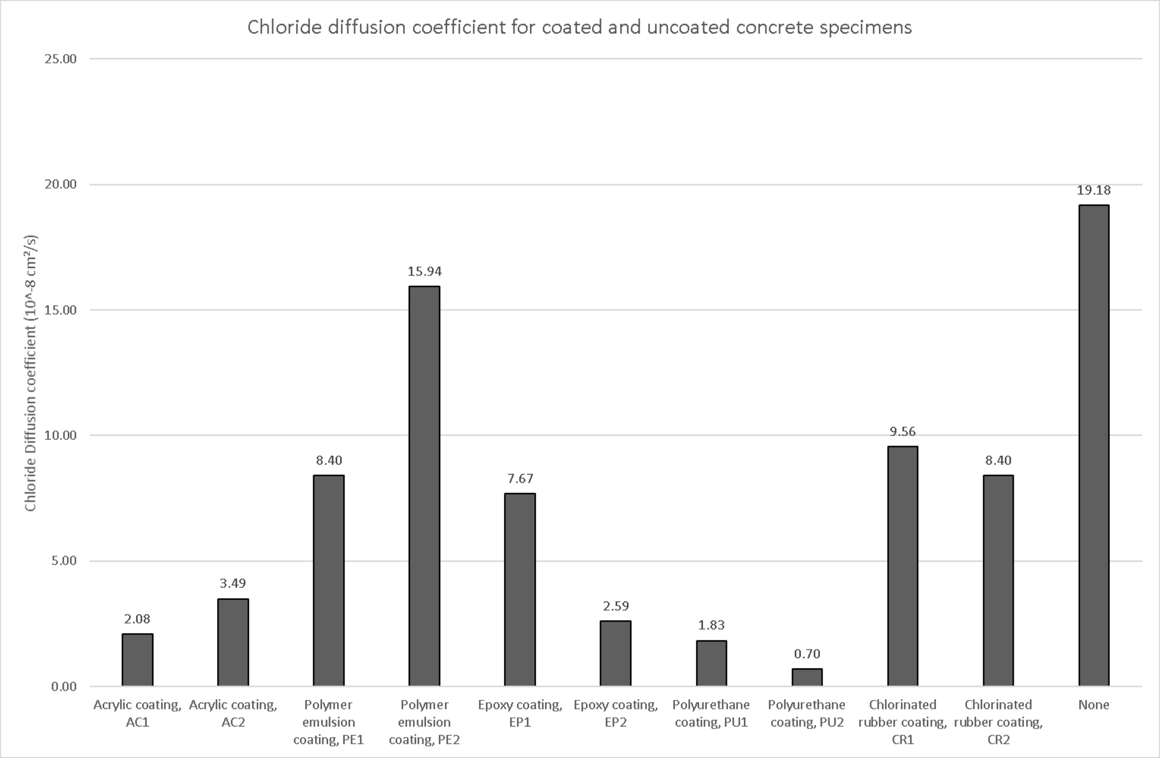


Figure 20: Chloride diffusion coefficients for coated and uncoated concrete specimens by Almusallam et al. (2003)

- Furthermore, they reported that the polyurethane and acrylic coatings were approximately 10 times more effective in resisting chloride ions than uncoated concrete specimens.
- They also calculated time to initiation of corrosion, using a concrete cover of 50 mm, to be 11 and 30 years (for the 2 polyurethane coatings) which was comparatively much better than other products tested, but also showed the vast variability in performance of different types of polyurethanes.

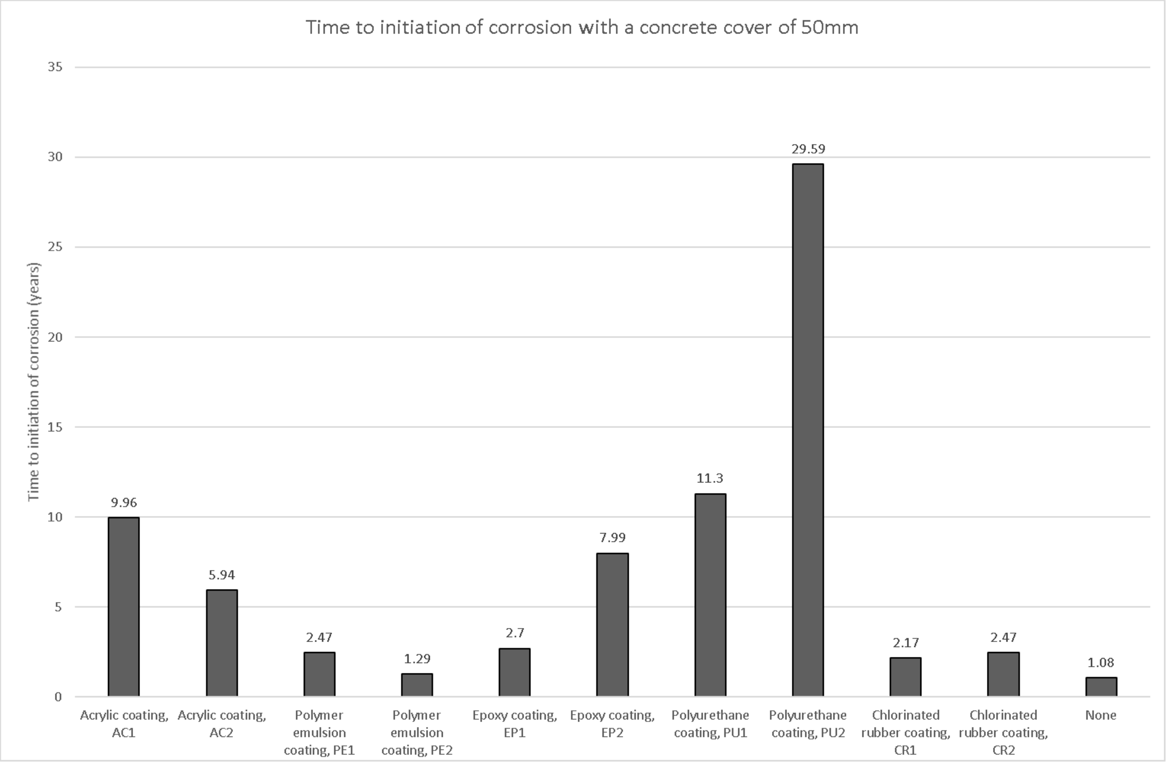


Figure 21: Time to initiation of corrosion with a concrete cover of 50mm of various surface coatings, by Almusallam et al. (2003)

- Water absorption was measured over 56 hrs on 50 mm diameter and 75 mm diameter test specimens. The two polyurethanes (PU1 and PU2) showed a 0.21% and 1.83% respectively, compared to the uncoated specimen whose absorption was measured to be 5% by weight. Although this is much lower than the uncoated specimen and suggests that the polyurethanes perform well in limiting water penetration, there is a large variation between the results of the 2 different suppliers. This was also evident for the acrylic coatings, epoxy coatings and chlorinated rubber coatings.
- In assessing the chemical resistance of these coatings, the authors submerged test specimens in 2.5% sulphuric acid and measured deterioration qualitatively on a scale of 1 – 5. Their results are represented in Table 19.
    - The authors concluded that the polyurethane and epoxy coatings performed better than the other coatings, having looked at electrical resistivity, water absorption and sorptivity, chemical resistance and chloride diffusion. However, they reported a wide variation in the performance of the 2 different coatings of the same generic type was found.
- It is further noted that the authors did not include a description of the types of polyurethanes used. As discussed previously, there are numerous different formulations of polyurethanes each of which can have differing properties. It is thus difficult to compare these results to other works.

Table 19: Deterioration ratings for coated and uncoated mortar specimens exposed to 2.5% sulphuric acid, by Almusallam et al. (2003)

Coating	**Deterioration rating, after (days)**				
	3	**7**	**21**	**30**	**60**
Acrylic, AC1	1	2	2	3	3
Acrylic, AC2	2	2	3	3	3
Polymer emulsion, PE1	3	3	4	5	5
Polymer emulsion, PE2	3	3	4	4	5
Epoxy, EP1	1	1	1	1	2
Epoxy, EP2	1	1	2	2	2
Polyurethane, PU1	1	1	1	2	2
Polyurethane, PU2	1	1	1	1	2
Chlorinated rubber, CR1	2	2	3	4	5
Chlorinated rubber, CR2	2	2	3	4	4
None	5	5	5	5	5

Ratings:

1	Coating intact
2	Corners damaged
3	Corners and Edges deteriorated
4	Corners, edges and some surface damage
5	Complete deterioration

Vipulanandan and Liu, (2005) tested two commercially available polyurethanes for chemical resistance in order to simulate sewer environments. They found that the two polyurethanes performed very differently.

- Different bond strengths were found and the two polyurethanes performed differently under wet surface and dry surface application conditions.
- One product was found to have a predicted increased service life of 14 times, and the other of 57 times, using a modified version of the ASTM G20 test method.

Awasthi and Agarwal (2007) investigated emulsion paints based on an IPDI polyurethane (cyclo-aliphatic) with a polyester backbone, an acrylic emulsion and a polyurethane-acrylic emulsion blend, all with a TiO_2 pigment. It is noted here that the authors provided more detailed information than most researches regarding the specific formulation of the polyurethane used, as shown in Table 20.

- They conducted half-cell potential tests after 8 months of exposure in corrosive environments and found the polyurethane emulsion to have performed the best compared to the 2 other coatings (an acrylic emulsion and a polyurethane-acrylic emulsion blend) and uncoated concrete.
- Mass loss of rebar was also investigated, and the polyurethane-acrylic blend paint was found to have performed marginally better than the polyurethane, which on its own also performed relatively well, reducing the mass loss by about 50% compared to the uncoated specimens.
- The chloride diffusion rates measured showed that the polyurethane and polyurethane-acrylic blend performed similarly well at reduced diffusion rates of 4 – 5 times less than the uncoated samples and 20% better than the acrylic emulsion.

- They finally concluded that the polyurethanes performed well under corrosion tests and that the polyurethane-acrylic blend performed better than the single monomer coatings.

Table 20: Characteristics of polyurethane dispersion used by Awasthi and Agarwal (2007)

Properties	Polyurethane Dispersion
Polyol backbone	Polyester
Charge	Anionic
Isocyanate used	IPDI
Isocyanate type	Cyclo-aliphatic
Chain extender	Ethylenediamine
Appearance	Milky White
Viscosity (cps) @30^o	41
pH	8.2
Solid (wt%)	30

Park (2008) studied carbonation of concrete in relation to degradation of concrete coatings. The author looked at permeation of carbon dioxide using a differential pressure method. The author set up a diffusion-reaction carbonation model which was then validated using tests on polyvinyl chloride (two-component heat hardening cured), polyurethane (one-component moisture cured), epoxy (polyamide, two-component heat hardening cured) and acrylic (melamine resin, two-component heat hardening cured) coatings.

- The author found that all the coatings reduced the decline of calcium hydroxide, and that more coatings had the effect of decreasing the depth of carbonation slightly due to diffusion in the region where calcium hydroxide had decreased.
- The author concluded that the protective performance of the coatings was as follows (in increasing protection): acrylic > epoxy > polyurethane > polyvinyl chloride.

Medeiros and Helene (Medeiros and Helene, 2009) studied surface treatments of reinforced concrete in marine environments and their influence on chloride diffusion and capillary water absorption, using several coating systems, as listed below.

1. Water dispersed silane/siloxane
2. Solvented silane/siloxane
3. Solvented acrylic
4. Polyurethane
5. Blend of 1 & 3
6. Blend of 2 & 3

- In studying both water permeability (using a pipete absorption test) and capillary action (sorptivity test), they found all surface treatments tested were highly effective in inhibiting water absorption by capillary action. And that the double systems and the polyurethane were more effective in inhibiting water penetration than the other systems.
- Using a rapid chloride penetration test according to ASTM C1202/97 and by determining diffusion coefficients, they found the polyurethane coating to be the most efficient, reducing chloride diffusion by 86%. They also noted that the moisture-cured silane/siloxane reduced the chloride coefficient by only 9%. The solvented silane/siloxane performed slightly better at 17% reduction. The acrylic coating presented 20% chloride reduction rate.

- Furthermore, they presented a service-life prediction based on chloride penetration and concluded that (with 40 mm cover) the polyurethane increased the estimated service life by 30.5 years, which was 7.8 times the uncoated reference of 4.5 years.
- It is further noted that the authors stressed the importance of understanding various test conditions' environments when comparing research. They also stressed the importance of understanding the specific composition of the polyurethane used (and by extension any other surface coating).

8.4 POLYMER MODIFIED CEMENTITIOUS COATINGS

8.4.1.1 Introduction

These coatings are typically based on a blend of ordinary Portland cement (OPC) and fine graded sand. A range of different additives will usually be used in order to control specific desired properties, such as pot-life, setting time, thixotropy, curing etc. They are often applied as renderings by trowel and protects by providing a physical barrier. They also provide good weathering resistance. They may also contain migrating substances which inhibits corrosion in the original concrete (Beckett *et al.*, 1987; Squirrell, 2002).

8.4.1.2 Historical Development of Polymer Modified Cementitious Systems

A detailed account of the development of this technology has been listed by Ohama (1995) and ACI Committee 548 (2003). A summary of the important milestones is listed below:

- 1923: Cresson develops the first patented polymer modified cement system. However, this patent was for pavers where cement was used a filler.
- 1924: Lefebure develops the first modern day type polymer-modified cement system using natural rubber latex.
- 1932: First use of synthetic rubber latex by Bond.
- 1939: Rodwell's patent uses synthetic resin latexes, including polyvinyl acetate latexes.
- 1940 – 1950: Some patents on polymer-modified systems with synthetic latexes, such as polychloroprene rubber latexes (Neoprene) and polyacrylic ester latexes published. Also, polyvinyl acetate modified mortar and concrete were actively developed for practical applications. Also, first uses on applications such as bridges, flooring and anti-corrosion.
- 1953: A patent for the use of redispersible polymer powders as polymer modifiers for hydraulic cementitious mixtures was applied for.
- 1960 – 1970: Styrene-butadiene rubber, polyacrylic ester and poly (vinylidene chloride-vinyl chloride) modified mortars and concretes become increasingly used in practical applications.
- 1967: The first use of epoxy resins as a cement modifier.
- 1960 Onwards: Considerable advancement in practical research and development of polymer-modified cements and mortars in various countries, particularly the USA, USSR, West Germany, Japan, and the UK.
- 1975: First International Congress on Polymers in Concrete

8.4.1.3 Uses of Polymers in Concrete

ACI Committee 548.1 (1997) and 548.3 (2003) differentiates between 3 diverse general uses of polymers in concrete, i.e.:

- Hydrated cement concrete, impregnated with a monomer that is polymerised in-situ – referred to as polymer impregnated concrete (PIC),
- A composite material where the aggregates are bound together in a matrix with a polymer instead of cement (although cement may still be as a filler) – referred to as polymer concrete (PC) and
- Ordinary Portland cement concrete combined at mixing stage with organic polymers that are dispersed or redispersed in water – referred to as polymer modified concrete (PMC).

Each of the above types can be used for repair purposes and improving the durability of structures. PIC can be used on precast elements and in-situ structures to improve durability and restore deteriorated structures. It functions by (partially) filling pore voids with polymers and creating a relatively impermeable zone thereby reducing permeability to water and aggressive agents. Full impregnation of pores is possible using vacuum pressure techniques, but such systems are used where strengthening is also a requirement and the added effort and cost is justifiable. They have been used on bridge, spillways and deteriorated building structures (ACI Committee 548, 1997).

However, most coatings are in fact mortars (i.e. without course aggregate) based on the PC and PMC type formulations. PMC coatings are the subject of the discussions in the following sections. More information on the different uses and properties of these types of polymers can be found in ACI 548.1R. However, this publication (ACI 548.1R) largely discusses polymer (normal, modified or impregnated) concrete in general, rather than polymer mortars or coatings specifically.

8.4.1.4 Modern Application

Polymer-modified concrete as defined above is sometimes referred to as polymer Portland cement concrete (PPCC) or latex-modified concrete (LMC). Specific types may also take different names such as latex-modified mortar (LMC) (ACI Committee 548, 1997, 2003).

Polymers can improve adhesion, flexibility (and therefore crack-bridging ability) and freeze-thaw resistance, abrasion resistance, flexural and tensile strength and reduce permeability of cementitious coatings whilst allowing the use of a low w/b ratios – producing high strength coatings. They can also increase resistance to water and salt penetration and reduce curing requirements (Leeming *et al.*, 1997; ACI Committee 548, 2003).

Organic polymers are thousands of simple molecules, called monomers, which through a polymerisation process combines to form larger molecules. They are available in three forms;

1. As a dispersion in water – called a latex,
2. As a redispersible powder or
3. As a liquid that is dispersible (soluble) in water

Many polymers are available on the market, of which only 5% is suitable for use with cement. A list of polymers used for cement is given in Table 21.

Table 21: Polymers used with Hydraulic Cement Mixes (ACI Committee 548, 2003)

Type	Polymer	
Elastomeric	Natural rubber latex	
	Synthetic latexes	Styrene-butadiene, polychloroprene (Neoprene), acrylonitrile-butadiene
Thermoplastic	Polyacrylic ester*, styrene-acrylic*, polyvinyl acetate*, vinyl acetate copolymers*, polyvinyl propionate, vinylidene chloride copolymers, polypropylene	
Thermosetting	Epoxy resin	
Bituminous	Asphalt, rubberized asphalt, coal-tar, paraffin	
Mixed latexes		

**Available in redispersible powder form*

The most commonly used polymers are (Leeming *et al.*, 1997; Squirrell, 2002; ACI Committee 548, 2003):

- Acrylic polymers and copolymers (PAE)
- Styrene-acrylic copolymers (S-A)
- Styrene-butadiene copolymers (S-B)
- Vinyl ester of versatic acid (VA-VEOVA)
- Ethylene vinyl acetate copolymers (VAE)
- Vinyl acetate homopolymers (PVA)

Properties of polymer modified concrete and mortars vary depending on the specific mixture formulation, type of polymer used and polymer-cement ratio. Therefore, selection of polymer type depends on specific desired properties and cost. Cost of polymers vary considerably but, in general, the cost of polymers from highest to lowest is as listed above i.e. PAE > S-A > S-B > VA-VEOVA > VAE > PVA. Some formulations do, however, possess good all-round performance (Squirrell, 2002; ACI Committee 548, 2003).

They are, however, typically sensitive to hot weather, low humidity and wind during curing and thus special precautions are required during application and curing – as premature water loss may occur. Thus pre-wetting (to saturated surface dry condition) is typically required. In general, it is important that the suppliers detailed instructions are followed, from mixing and proportioning to application requirements (Leeming *et al.*, 1997).

Commercially these coatings are typically supplied as two-pack products. Single-pack formulations are also available, with polymers included in a dispersible form. They can be applied via brush, trowel or spray, giving coatings up to 2 mm thick (Leeming *et al.*, 1997).

8.4.1.5 Cement Hydration with polymerisation

The pore structure formation of polymer modified cementitious mixtures are influenced by two main processes i.e. hydration of cement and coalescing of the polymer.

Cement hydration occurs first, followed by the coalescing of the polymer. A co-matrix of cement and polymer film is formed which results in superior pore structure and properties compared to conventional cementitious mixtures. A simplified model as offered by Ohama and presented by ACI 548.3 is shown below.

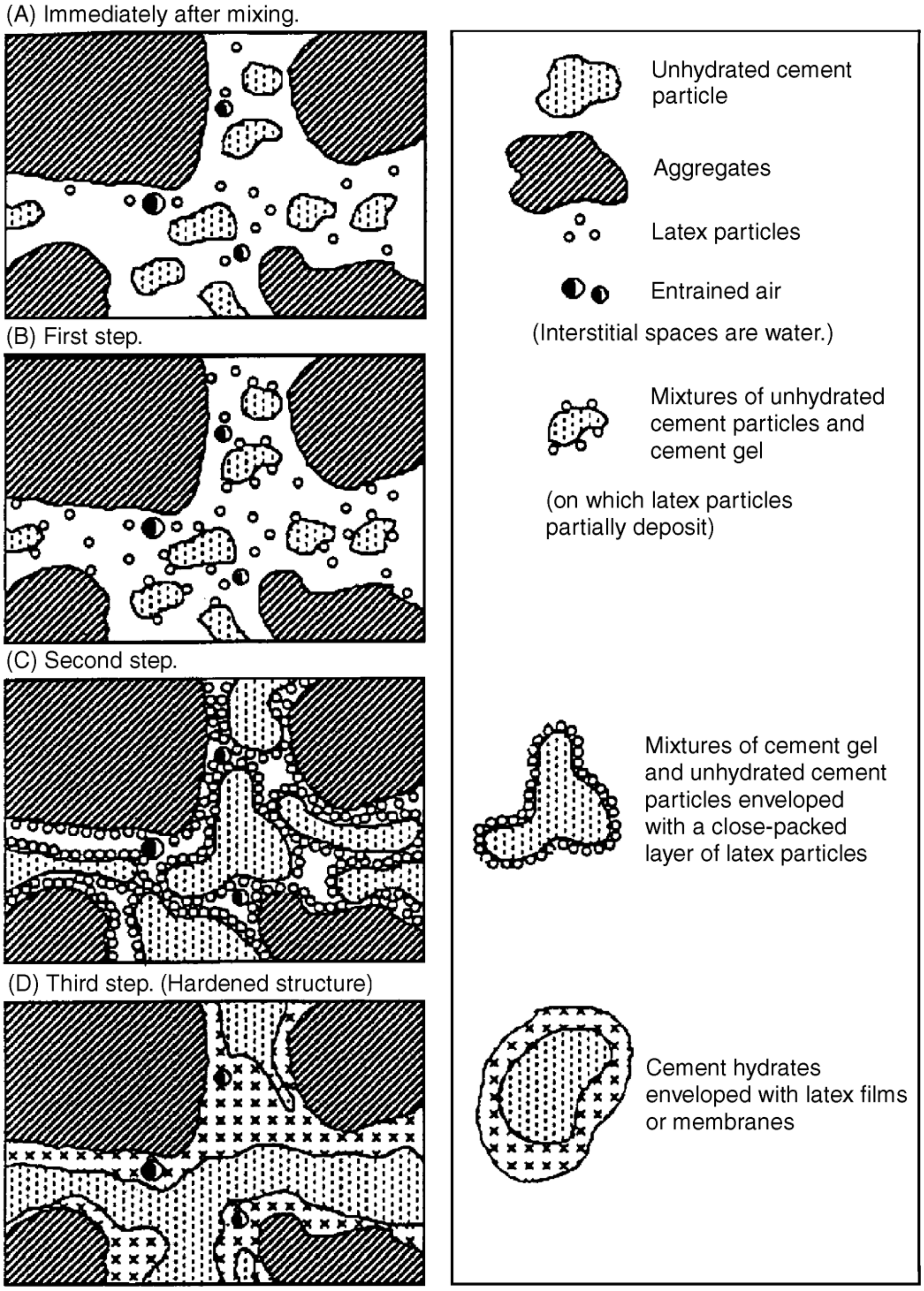
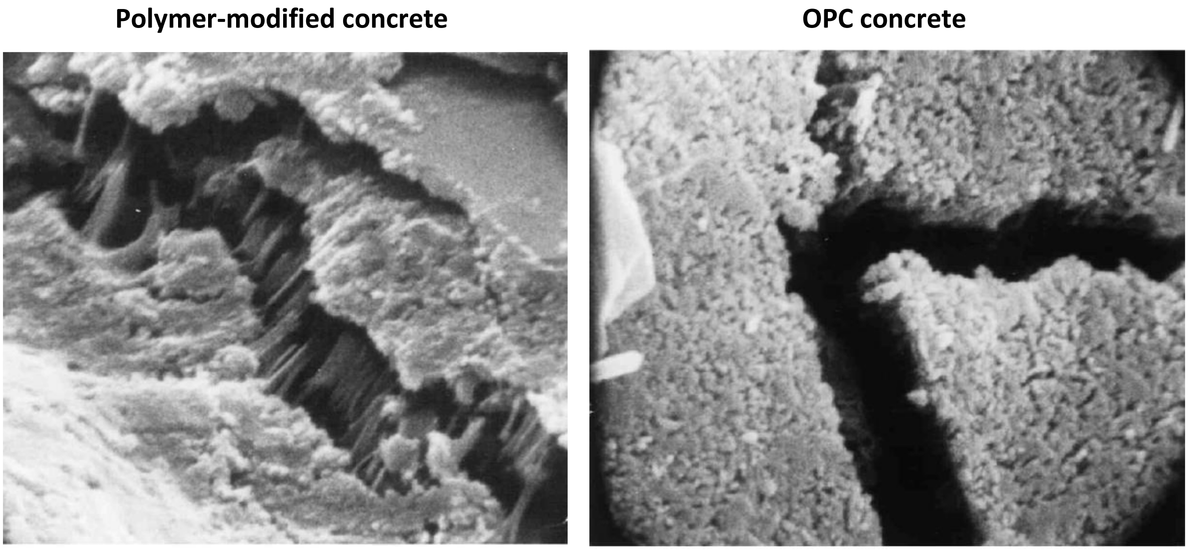


Figure 22: Simplified model of formation of polymer-modified cement co-matrix (Ohama, 1998; ACI Committee 548, 2003)

An electron micrograph of a micro-crack in conventional concrete versus PMC is shown in Figure 23. One clearly sees the polymer strands bridging the microcrack in the PMC. This results in increased tensile and flexural strength (and therefore less cracking), reduced fluid ingress, increased chemical resistance and freeze-thaw action (ACI Committee 548, 2003).



Polymer-modified concrete

OPC concrete

Figure 23: Electron micrographs of polymer-modified and ordinary Portland cement concretes at 12000x magnification (ACI Committee 548, 2003)

The polymer modification process involves firstly cement hydration followed by the coalescing of the polymer.

As cement hydration occurs, and hardening ensues, the polymer particles become concentrated in the void spaces. As water is removed due to hydration and evaporation, the polymer particles coalesce into a film that is interwoven with the cement hydrates. This produces a polymer-cement comatrix that coats aggregate particles and lines interstitial voids (ACI Committee 548, 2003). This process is depicted in Figure 22.

PMC does not produce bleed water unlike conventional concrete mixes, but is prone to plastic shrinkage due to the water reducing effect of the polymerisation process. This may occur due to polymer particles coalescing before sufficient cement hydration occurs causing the cement paste to shrink before the concrete has sufficient tensile strength to restrain cracking.

8.4.1.6 Properties and Performance of Common PMC's

Modern concrete technology allows for coatings of these type to be formulated for very specific functions. Some formulators manufacture general purpose coatings that exhibit good all-round performance (Squirrell, 2002).

Some common types of polymer-modified coatings are listed below;

- Fibre-Reinforced Coatings
- Styrene-Butadiene Latex
- Acrylic Latex
- Epoxy Polymer Modifiers
- Redispersible Polymer Powders

Detailed information on these coatings can be found in ACI 548.1 and ACI 548.3. Some general properties of common PMC's are given in Appendix C.

9 INDUSTRY REVIEW

This section is a record of an industry review conducted by the author by interviewing representatives of two of the most prominent concrete surface protection product suppliers in the Western Cape (Sika and A.B.E. Construction Chemicals), which can also be taken as indicative of the South African market in general.

9.1 A.B.E. CONSTRUCTION CHEMICALS

The information in this section is taken from the A.B.E. Construction Chemicals (ABE) catalogue (2014) as well as the case study conducted with ABE representative Brett Papayanni (see Appendices).

ABE lists the following protective treatment products and brief descriptions in their product catalogue:

Product Name	Product Type	Uses	Properties
Duracote WB	Acrylic	Carbonation, chloride and other waterborne contaminants barrier	Coloured, UV stable, flexible
ABE Silocote	Cementitious	Concrete, masonry structures, protection against carbonation, chloride and other waterborne contaminants barrier	Elastomeric, crack bridging, UV stable
Dura.sil SH	Silane-Siloxane	Water repellent for concrete and masonry	Prevents moisture & soluble salt ingress, breathable
MuCis mia 100	Multi-compound	Migrating corrosion inhibitor	Protects steel from cathodic and anodic reaction
ABE.Cote SF 356	Coal tar epoxy	Coating/mortar for protection of asphalt against oil & chemical resistance to concrete and steel	Good wear and chemical resistance

A detailed discussion of each product is given below:

9.1.1 DURACOTE WB

The Duracote WB is a water-based system (WB) pure aliphatic acrylic polymer. The system comes with a specially made primer (Duracote WB primer) which is applied at least 12 hours prior to application of the actual Duracote WB coating. The primer contains an acrylic resin with silane-siloxane molecules, which the system hydrophobic and barrier properties. The system is noted to be sensitive to weather (rain, frost, wind and dust) during application – which is perhaps partly due to the silane-siloxane incorporation. It is noted to have high elastomeric crack-bridging capabilities of up to 2 mm. it is noted to inhibit the passage of water and corrosive contaminants.

The above-mentioned properties appear to be typical of aliphatic polymers with the addition that they are noted to be UV stable – Aliphatic polymers are known to be very sensitive to UV exposure. It is, of course, not possible here to establish the extent of effectiveness. This is perhaps an example of the formulator improving the general properties of a system to give it more broad usage by negating known problems of the main active film forming protective compound.

9.1.2 ABE SILOCOTE

The ABE Silocote is a two-component polymer modified cementitious coating. It has been formulated specifically for use on internal and external surfaces of silos. Their general protective properties make them suitable for a range of different other uses as it is noted to withstand high hydrostatic pressures, limit the ingress of carbon dioxide, sulphates and chlorides. It can also bridge cracks of up to 0.3 mm (which is greater than maximum allowable crack width for water retaining structures of 0.2 mm, from BS 8007: 1987 – which is the code that has generally been used in South Africa). The product is easy to mix and use on site.

For external uses this product may produce different aesthetic appearances due to varying curing conditions, which may be a problem in certain situations.

9.1.3 DURA.SIL SH

This is a single-component silane-siloxane hydrophobic coating that can be used on masonry, some natural stone and concrete. Its properties are typical of silane-siloxane treatments and is listed below, as indicated the ABE catalogue:

- “Effective on new or old structures.
- Inhibits penetration of soot and grime, reduces unsightly staining.
- Easily applied by brush or spray.
- Preserves natural colour and texture of treated surfaces.
- Excellent water repelling properties.
- Colourless.
- Excellent resistance to weathering.
- Water vapour permeable, breathable.
- Significantly reduces water absorption.
- No discolouring or staining.
- Reduces water and chloride intrusion.
- Reduces efflorescence.
- Allows water vapour to migrate from structure”.

9.1.4 ABE.COTE SF 356

ABE.Cote SF 356 is a two-component solvent free amine-cured epoxy tar. It is primarily used as a high-build coating for chemical resistance and is used on asphalt surfaces to protect against oil attack. It can also be used for concrete by diluting with thinners. It can be used as a mortar by the addition of silica sand to make a screeding type mortar.

It provides chemical resistance to a range of harsh substances, such as:

- Distilled water,
- Sewage sludge, effluent water
- Aliphatic solvents,
- Acids: 35% sulphuric acid, 37% hydrochloric acid, 5% nitric acid, 10% acetic acid,
- Alkalis: 40% sodium hydroxide, 17% ammonium hydroxide

It is however not suitable for use with drinking water and food items. It also has a black coloured finish. The availability of other coatings specially formulated for use on concrete as well as the black colour finish may severely limit its uses.

9.1.5 ABE CASE STUDIES

In an interview conducted with ABE representative Brett Papayanni (see Appendix A), the following important notes were made:

- Pure silanes are not commonly used, except where specifically required. For most applications, where hydrophobic treatment is required, silane-siloxane blends are more cost effective whilst also still providing the required properties.
- Silane-siloxanes used as a surface treatment are very cost-effective surface treatments.
- The Duraflex coating is a twin-pack cementitious water proofing slurry, which is not listed in the ABE catalogue. It is a useful surface treatment system which has been used successfully on previous projects. This also highlights the need for engineers to discuss requirements with suppliers (rather than simply selecting from a catalogue) the project requirements and possible alternative solutions.
- Duracote WB is a decorative and flexible acrylic coating. It has been successfully used on structures in highly aggressive environments. It has a high crack-bridging capability of up to 2 mm, whilst also providing a consistent smooth paint like appearance. It is suggested that maintenance be undertaken every 5 – 10 years using this system.
- ABE’s Silocote is a polymer modified cementitious coating which was specifically formulated for use on silos, and has been shown to have a good track record in past applications and more recent ones. The system can be used for other applications where similar performance characteristics are required.
- Polymer-modified cementitious coatings (such as Silocote and Duracote) are commonly used, general purpose coatings with good durability-enhancing properties. However, the selection of treatment system and product may vary are very much depends on the specific required performance characteristics of the project or application.

9.2 SIKA

The information in this section is taken from the Sika product catalogue (2016) as well as the case study conducted with Sika representative Anthony Webster (see Appendix B).

Sika lists the following concrete protective treatment systems and brief descriptions in their product catalogue:

Name	Type	Product Application
Sika FerroGard-903 Plus	Migrating corrosion inhibitor	A migrating impregnation which absorbs onto re
Sikagard-703W	Silane-Siloxane	Provides a clear, water repellent surface on concrete and mortar
Sikagard-705L	Silane Liquid	Provides a clear, water repellent surface on reinforced concrete surfaces, preventing ingress of chloride ions
Sikagard-706 Thixo	Silane Crème	Provides a clear hydrophobic barrier to ingress of water and pollutants, especially chloride ions
Sikagard-550W Elastic	Acrylic	For protecting cementitious substrates against weathering and deterioration from aggressive environments

Additionally, the following waterproofing mortars are also listed. These are in-fact polymer-modified cementitious products and is often used as surface treatment systems.

Name	Type	Product Application
SikaTop-Seal-107 ZA	Polymer modified cementitious mortar slurry	A protective waterproof coating on interior or exterior concrete or mortar
SikaLastic-152	Fibre reinforced, polymer modified cementitious mortar	For waterproofing and protection of hydraulic structures like water storage tanks, concrete pipes, bridge parapets, water canals etc. 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

A detailed discussion on Sika's commonly used coatings are given below, taken from Appendix B:

Sikagard-550 W Elastic – This is an acrylic coating with excellent crack bridging capabilities. It is intended for use on external / outdoor surfaces where there is a risk of cracking. The system can be pigmented to almost any colour and will provide a consistent colour throughout the structure. This product / system also complies with EN 1504-2, and can be used for Principles 1,2 and 8 of EN 1504-9.

SikaTop-Seal-107 ZA – This is a two-component, waterproofing, polymer modified cementitious mortar. It is a rigid coating, and will seal inactive fine hairline cracks but has no real crack-bridging ability. It also complies with EN 1504-2 requirements for protective coatings and can be used for Principles 1, 2 and 8 of EN 1504-9. This is used in practice where contractors were unable to achieve project requirements for concrete finishes to create a uniform final appearance, or to fill blowholes and pinholes. Unlike the acrylic coating where the colour finish is likely to be uniform, cementitious coatings may vary from batch to batch and may differ due to curing conditions at the time. This may be a consideration is selection of protection system, particularly for outdoor external use. It is also said to protect against carbonation, freeze-thaw and de-icing salts and will increase water penetration resistance.

SikaLasic-152 – This is a flexible two-component cementitious mortar modified with alkali resisting polymers, fibres and microsilica. It is particularly useful for humid environments, low temperatures and where flexibility of cementitious coating is required. Unlike the acrylic coating where the colour finish is likely to be uniform, cementitious coatings may vary from batch to batch and may differ due to curing conditions at the time. This may be a consideration is selection of protection system, particularly for outdoor external use. It also meets the requirements of EN 1504-2 and can be used for Principles 1,2 and 8 of EN 1504-9.

Sikagard-703W – This is a silane-siloxane blend water repellent for use on concrete and mortar. A pure silane is also available both in liquid (Sikagard705L) and cream form (Sikagard706 Thixo). The silane cream is recommended for use in hot and wind regions. However, these are not as commonly used, largely due to the higher costs of pure silanes. A pure silane such as Sikagard706 Thixo can cost up to 270% more (per square metre) than a silane-siloxane such as Sikagard-703W. it is also the least expensive of the above-mentioned coatings. However, it should be kept in mind that these coatings are colourless and transparent and as such will not cover or correct defects in the concrete surface nor will it be able to bridge and cracks (active or not).

Chemically the main difference between the silane and a silane-siloxane blend, is the solids content of the products. The silane-siloxanes are sold as low end hydrophobic barriers for masonry and concrete surfaces, where a high degree of protection is not required. This ‘blend’ is to make the products less volatile and easier to use. These products typically have a range of solids content between 7 – 15%.

The use of silanes are specifically intended for marine environment or areas where a high degree of protection is required. The pure silane is far more volatile than the blend of silane-siloxane products. This is the reason Sika has two versions of the silane; the liquid Sikagard-705L and the cream version, the Sikagard-706 Thixo.

These products, Sikagard-705L and Sikagard-706 Thixo, have a solids content of approximately 100% and 80% respectively. This is why there is a large difference in price and a huge difference in effectiveness between the low end silane-siloxane and the pure silane (high solids content products).

SikaFerroGard-903 Plus – This is a surface applied migrating corrosion inhibitor.

Additionally;

- Acrylics will provide a consistent single colour finish, whereas with cementitious coatings, the final colour may vary from batch to batch of concrete and curing conditions at different times of application.
- In many cases time constraints is an important consideration for contractors and applicators, Contractors would often favour coatings where the time to application or overcoating is less.

10 DISCUSSIONS, CONCLUSIONS AND OUTLOOK

This literature review has provided a brief overview of deterioration mechanisms and transport properties of concrete. It also provided a detailed overview of surface protection system in general, their classification, selection, usage and performance. Several important surface treatment systems (silicates, cementitious, silanes and siloxanes and polyurethanes) have been discussed in detail, as well as some lesser used systems such as stearates and drying oils.

The following dialogue discusses important points highlighted in the main body of the report, and summarises outcomes of the main objectives. It is intended to record points of interest and provide a proposal for a way forward in terms of research and practice.

10.1 HISTORICAL BACKGROUND TO AND LATEST DEVELOPMENTS OF CONCRETE SURFACE COATINGS

An overview of the historical background of the use of the various surface treatments, where information was available, was given. A somewhat detailed historical overview was given for the silicate type, polyurethane and polymer modified cementitious coatings – as these coatings were discussed in more detail. Whilst some context was provided for some other types of coatings, such as the silanes and siloxanes. Brief comments were made regarding selected other coatings mentioned in this report (such as the epoxies).

The historical background together with understanding the protective action and chemical nature of generic products provides a good platform for understanding the possible use of any type of treatment and its limitations. The industry review provided further supportive information for current industry usage. It was not possible, in a work such as this, to provide an in-depth detailed review of each treatment type mentioned in this work; however, appropriate information was given to provide a basic understanding of the development of selected systems. Additionally, the latest available research for each system has been provided, specifically highlighting its potential to improve various aspects of concrete durability.

The polymer modified cementitious coatings polyurethanes and silane/siloxane surface treatment systems appear to be the most popular and is already widely used, in various forms, in industry. In particular, PMC coatings appear to be the most versatile and most used coating.

Also, as mentioned in this work, South Africa has no commercially available guidelines for the use various surface treatments. In order to work towards such a set of guidelines, a detailed historical background review for each system needs to be undertaken.

10.2 USE OF SURFACE PROTECTION SYSTEMS

10.2.1 SELECTION OF SURFACE TREATMENT

The selection of a surface treatment was noted to be a complex matter, since there are many factors to consider which may differ from project to project and in different exposure conditions. It is important for design engineers to have a good working understanding of the basic deterioration mechanisms, transport properties and the functioning of different types of surface treatment systems. For a successful application design engineers need to provide unambiguous specifications, so that contractors have a clear understanding of project requirements. There is thus a need to provide guidelines and a framework for engineers for selecting a treatment system.

Collaboration between design engineer and supplier can assist in pre-selection of surface treatment.

10.2.2 SURFACE TREATMENT CLASSIFICATION

Surface treatment systems are commonly classified by their protective action. This is the approach used by EN 1504 and ACI and appears to be the most intuitive method. The EN 1504 convention has been used in this document which uses three broad categories:

- Hydrophobic Impregnation
- Impregnation
- Coatings

The author has suggested that the third category could be split into thin "Coatings" of 0.1 mm to 5 mm thickness (as suggested by Note 1 of EN 1504-1), and "Overlays" of greater than 5 mm thickness. This will differentiate between "coatings" which provide protection by the formulation and interaction with existing concrete surface and "overlays" which may provide protection by actually increasing the cover (even if their formulation may also provide additional effective cover). "Overlays" may be implemented using different types of products, such as Sika and ABE's repair mortar ranges and may also typically have a coating (hydrophobic impregnation, impregnation or coating) applied over it.

10.2.3 HYDROPHOBIC IMPREGNATION

Hydrophobic Impregnation is commonly achieved by the use of silanes or siloxanes or silane-siloxane blends. In particular, and as discovered in the industry review, silane-siloxane blends are more commonly used. This is due to cost, difficulties in application of silanes, and environmental concerns with the VOC content of silanes.

The excellent hydrophobic properties and breathability of silanes and siloxanes makes them a very preferable option for use in improving durability of concrete, particularly where an unchanged appearance is desirable. However, its lack of crack-bridging ability limits its usage – but can still be used where a flexible coating is applied first as part of a duplex system.

10.2.4 SILICATE PAINT TECHNOLOGY

Silicate (Sodium and Potassium) paint technology has been in use since the 1960's. They are typically used for cement clinker production and floor hardeners and little research is available on their use as concrete surface protection systems to improve durability. There are also conflicting results in literature. Most of the reports suggest that silicate sealants should not be used as a surface protection system to improve the durability of concrete structures. The conflicting reports necessitates more research to be done on this material. It may be that some types of formulations are not adequate or that silicates paints are not adequate in certain conditions i.e. the differences in reports need to be reconciled. Particularly, the nature of the proposed protection mechanism needs to be understood. Some researchers have suggested that this depends on the product or formulation type.

This will give researchers, engineers, contractors and clients a better insight into the proposed usage of silicate sealants. In the meantime, it is advisable that, should silicates be considered for a particular application, they should be screened and some testing should be carried out to check the effectiveness of the product for the particular project requirements.

10.2.5 POLYURETHANES

Polyurethanes are available in many different forms. Some researchers have pointed out the difficulty of comparing results where insufficient information was provided on the material composition or the different exposure conditions were used. Large differences in performance of the same generic type of polyurethane was found between different suppliers.

Generally, research has shown most polyurethane products to possess the ability to significantly increase the service-life of concrete structures. Polyurethanes have been shown to be effective in;

- Inhibiting water absorption by capillary action,
- Significantly reducing chloride diffusion
- Decreasing the effect of carbonation
- Reducing the rate of corrosion
- Protecting against (sulphuric) chemical attack

10.2.6 CEMENTITIOUS COATINGS

Polymer-modified cementitious coatings (or PMC) are the most commonly available and used surface treatments. They appear to be fairly versatile products, where specific desired properties can be formulated by a supplier. The properties of PMC coatings will depend on the type of polymer used, the polymer-cement ratio used and their formulation. Some are known to have good all-round properties. This is further evidenced by the Industry Review (see Chapter 9), where both Sika and ABE have a small selection of PMC mortars which are said to have various desired properties – including those related to application, durability of the concrete substrate and the coating durability as well.

As their properties can vary considerably it is important to follow the supplier's application and use guidelines and consultation with the supplier is advised. Due to the additional polymerisation process during curing, they may typically be sensitive to weather, low humidity and wind and therefore may require special precautions when used. Pre-mixing to surface saturated conditions is also generally required.

10.3 ADOPTION OF EN 1504

Guidelines and prescriptions given by EN 1504 and ACI have been discussed in this work. It was noted that there are no repair standards in South Africa, and guidance on treatment systems can only be found in specialist literature. Since South Africa is in process of adopting the Eurocode (specifically EN 206 and EN 1992) for concrete design, the implementation of the European repair code EN 1504 should also be considered.

Notwithstanding the proposed adoption of EN 1504, both EN 1504 and the ACI Concrete Repair Manual were noted as having an extensive library of information and guidelines for the evaluation, selection, usage and implementation of various treatment systems which would be useful to clients, engineers, contractors and applicators. In the absence of a formalised repair standard, it is recommended that EN 1504 procedures be used as the basis for any repair project.

10.4 APPLICATION GUIDELINES

Generalised application guidelines have been provided. It was also noted that, in general, product supplier instructions should be followed for application, as guidelines may vary by formulation and is affected by any additives that may have been used by the formulator.

Additionally, the ACI Concrete Repair Manual documents are a very good source of information for surface treatments. The ACI Concrete Repair Manual has an extensive library of information on various products and systems and can be used as a benchmark for the development of guidelines in South Africa. This requires further research efforts beyond this initial work.

10.5 INDUSTRY REVIEW

An industry review was undertaken in which surface coating products and recent applications of the two largest local surface coating suppliers' in South Africa were reviewed. Due to the limitations of this work, this section was necessarily brief. However, the information gained offered useful feedback and provides a context for this literature review in light of South African conditions, products and treatment system availability and usage.

Silane-siloxane blends were noted to be much cheaper than the pure silanes, and is therefore used more often. Silanes are only used in very special circumstances, where the very high cost of the material is justified, crack-bridging is not an important requirement and other alternatives are not viable, such as on the Cape Town Stadium, where the time to the upcoming 2010 FIFA World Cup meant that a high-performance repair or surface coating solution that was the least time consuming was required to meet the project quality and time constraints. This likely ruled out a demolish-and-reconstruct option as well as a surface coating which required extensive application and curing time.

Polymer-modified cementiotious coatings of various forms are available and typically provide for a wide variety of applications, even those specially formulated for specific applications. These are the most used type of surface treatment systems.

A comprehensive (perhaps dedicated) industry review is required going forward. Should South Africa move towards adopting EN 1504, such a study would be of great benefit to the industry as a whole. A move towards a new standard such as this may very likely require a strong argument in favour of doing so, and needs to be based on documented research. Therefore, research going forward is also needed to document and assess the number, extent and reasons of failed surface coating applications in South Africa, as well success stories.

10.6 WAY FORWARD

- More research is needed to assess current problems in industry related to the selection, use and application of surface treatments systems in South Africa.
- More research is required to assess, compile and publish guidelines on the use of various surface treatments systems commonly used in South Africa.
- Clients, engineers and contractors should adopt EN 1504 procedures for future repair projects.
- South Africa should consider and follow through with the adoption of EN 1504.

11 APPENDICES

(see following pages)

APPENDIX A: SUPPLIER REPORT 1: A.B.E CONSTRUCTION CHEMICALS

Course:	CIV5017Z: Dissertation		
Dissertation Title:	Protective Coatings for Concrete Structures		
Recorded In:	Appendix A		
Interviewer & Author:	Luqmaan Jappie	**Student Number:**	JPPLUQ001
Supplier Name:	A.B.E. Construction Chemicals		
Supplier Representative:	Brett Papayanni		
Date:	06 December 2017		

INTRODUCTION

This document serves as a report by the author on the industry review undertaken as part of the above-mentioned dissertation. This part of the dissertation is intended to report on current industry norms in the selection and use of protective coatings for concrete structures in South Africa. This particular document is a record of the discussions between the author and A.B.E. Construction Chemicals' representative, Brett Papayanni.

COMMONLY USED PROTECTIVE TREATMENT SYSTEMS

Durasil SH – This is silane-siloxane blend and as such it is cost-effective. It is perhaps the most cost-effective of the coatings listed here as it is used for water repellence and not water retaining – the cementitious coatings can be used for this purpose. It is also said to require little-to-no maintenance over its intended lifespan. Another major advantage is that it does not change the appearance of the concrete. Pure silanes are not commonly used in practice mainly due to the cost of pure silanes and as such, is not part of ABE's product selection.

Duraflex – This is a twin-pack cementitious water proofing slurry. It is waterproof and can bridge cracks up to 200μm.

Silocote – This is a twin-pack cementitious water proofing slurry, developed specifically for coating of silos but can and has been used for other purposes. The Silocote is a flexible and decorative coating and provides an off-white concrete finish. Silocote has a grainy sand like texture when cured due to the sand aggregate in the mix.

Duracote WB – This is a decorative acrylic coating. It was specifically designed to be a flexible crack-bridging protective coating and can bridge cracks up to 2 mm. It provides a smooth finish and has been used successfully on bridges. It is not as commonly used as the other above coatings listed.

ABE Cote SF356 – This is a solvent free two-part epoxy tar coating used to provide chemical resistance. It can be used on concrete, steel and asphalt. It is specifically only used for concrete in sewer environments.

CASE STUDY OF TRANSNET SALDANHA PORT INFRASTRUCTURE REPAIRS

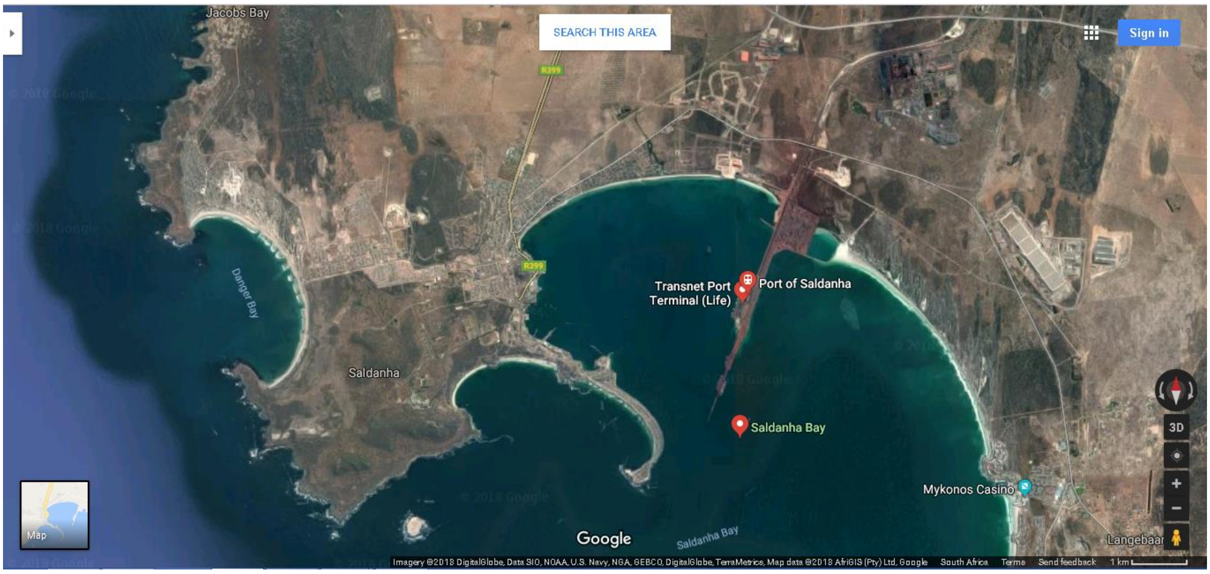


Figure 24: Google Map Satellite View of Saldanha Port (Google Maps, 2017)

Figure 25: Saldanha Port Birds View (Google Maps, 2018a)

This project required repairs of Transnet's concrete infrastructure at the Saldanha Port. The existing infrastructure had deteriorated and had led to spalling due to reinforcement corrosion, due to the harsh marine exposure conditions. The requirement was to repair spalled areas and provide a protective coating to the concrete infrastructure.

The Silocote and Duracote WB (with grey pigment) was considered for use as surface protection systems. However, the Duracote WB was selected as it was more appropriate for the exposure conditions. Additionally, the Duracote has a much higher crack bridging capability (1.8 mm to 2.0 mm) compared to that of the Silocote (static cracks up to 0.3 mm). Another consideration was that the Duracote provides a smoother paint-like appearance, whereas the Silocote provides a rough textured finish.

Using this particular system, maintenance should be carried out every 5 – 10 years, depending on conditions. To-date the system has performed well.

CASE STUDY OF SNOWFLAKE SILO RECOATING

Figure 26: Google Street View of Snowflake Grain Silos (Google Maps, 2017)

This project entailed the recoating of the Snowflake silos in Salt River, Cape Town. The coating was required as maintenance and specifically needed to prevent water ingress in the grain silos.

The environmental exposure condition is largely exposed to carbon dioxide, however, may be subjected to some airborne chlorides, owing to the proximity to the ocean and the height of the silos which is unimpeded. The project required the external surfaces of the silos to be cleaned and coats of Silocote applied. No alternatives were considered since the Silocote was specifically formulated for coating of silos, and has an excellent track record.

CASE STUDY OF SALT RIVER BRIDGE REPAIRS

Figure 27: Google Street View of Salt River Bridge (Google Maps, 2018b)

This project entailed the repair of the Salt River bridge on the R27 for Transnet. The bridge is in marine exposure conditions and has the Salt River flowing beneath.

Some spalling was repaired and the entire structure was then overcoated with Duraflex. The Duraflex provided a consistent pleasing aesthetic appearance whilst also providing the required performance criteria requested by the client. The particular system could be overcoated after a few years as required by regular on-going inspection.

The high winds and salt build-up on the concrete surface was noted as a particular problem on site, for application of the coating.

APPENDIX B: SUPPLIER REPORT 2: SIKA

Course:	CIV5017Z: Dissertation		
Dissertation Title:	Protective Coatings for Concrete Structures		
Recorded In:	Appendix B		
Interviewer & Author:	Luqmaan Jappie	**Student Number:**	JPPLUQ001
Supplier Name:	Sika		
Supplier Representative:	Anthony Webster		
Date:	09 November 2016 and 11 November 2017		

1 INTRODUCTION

This document serves as a report by the author on the industry review undertaken as part of the above-mentioned dissertation. This part of the dissertation is intended to report on current industry norms in the selection and use of protective coatings for concrete structures in South Africa. This particular document is a record of the meetings (09-11-2016 & 11-11-2017) and site visit (09-11-2016) between the author and Sika's representative, Anthony Webster.

COMMONLY USED PROTECTIVE TREATMENT SYSTEMS

Sikagard-550 W Elastic – This is an acrylic coating with excellent crack bridging capabilities. It is intended for use on external / outdoor surfaces where there is a risk of cracking. The system can be pigmented to almost any colour and will provide a consistent colour throughout the structure. This product / system also complies with EN 1504-2, and can be used for Principles 1,2 and 8 of EN 1504-9.

SikaTop-Seal-107 ZA – This is a two-component, waterproofing, polymer modified cementitious mortar. It is a rigid coating, and will seal inactive fine hairline cracks but has no real crack-bridging ability. It also complies with EN 1504-2 requirements for protective coatings and can be used for Principles 1, 2 and 8 of EN 1504-9. This is used in practice where contractors were unable to achieve project requirements for concrete finishes to create a uniform final appearance, or to fill blowholes and pinholes. Unlike the acrylic coating where the colour finish is likely to be uniform, cementitious coatings may vary from batch to batch and may differ due to curing conditions at the time. This may be a consideration is selection of protection system, particularly for outdoor external use. It is also said to protect against carbonation, freeze-thaw and de-icing salts and will increase water penetration resistance.

SikaLasic-152 – This is a flexible two-component cementitious mortar modified with alkali resisting polymers, fibres and microsilica. It is particularly useful for humid environments, low temperatures and where flexibility of cementitious coating is required. Unlike the acrylic coating where the colour finish is likely to be uniform, cementitious coatings may vary from batch to batch and may differ due to curing conditions at the time. This may be a consideration is selection of protection system, particularly for outdoor external use. It also meets the requirements of EN 1504-2 and can be used for Principles 1,2 and 8 of EN 1504-9.

Sikagard-703W – This is a silane-siloxane blend water repellent for use on concrete and mortar. A pure silane is also available both in liquid (Sikagard705L) and cream form (Sikagard706 Thixo). The silane cream is recommended for use in hot and wind regions. However, these are not as commonly used, largely due to the higher costs of pure silanes. A pure silane such as Sikagard706 Thixo can cost up to 270% more (per square metre) than a silane-siloxane such as Sikagard-703W. It is also the least expensive of the above-mentioned coatings. However, it should be kept in mind that these coatings are colourless and transparent and as such will not cover or correct defects in the concrete surface nor will it be able to bridge and cracks (active or not).

Chemically the main difference between the silane and a silane-siloxane blend, is the solids content of the products. The silane-siloxanes are sold as low end hydrophobic barriers for masonry and concrete surfaces, where a high degree of protection is not required. This 'blend' is to make the products less volatile and easier to use. These products typically have a range of solids content between 7 – 15%.

The use of silanes are specifically intended for marine environment or areas where a high degree of protection is required. The pure silane is far more volatile than the blend of silane-siloxane products. This is the reason Sika has two versions of the silane; the liquid Sikagard-705L and the cream version, the Sikagard-706 Thixo.

These products, Sikagard-705L and Sikagard-706 Thixo, have a solids content of approximately 100% and 80% respectively. This is why there is a large difference in price and a huge difference in effectiveness between the low end silane-siloxane and the pure silane (high solids content products).

SikaFerroGard-903 Plus – This is a surface applied migrating corrosion inhibitor.

1.1 ADDITIONAL NOTES

- Acrylics will provide a consistent single colour finish, whereas with cementitious coatings, the final colour may vary from batch to batch of concrete and curing conditions at different times of application.
- In many cases time constraints is an important consideration for contractors and applicators, Contractors would often favour coatings where the time to application or overcoating is less.

CASE STUDY OF CAPE TOWN STADIUM

The project entailed the construction of a new sports stadium for the then upcoming FIFA World Cup 2010, and was completed in 2010. The site is located at Greenpoint, approximately 450m from the Atlantic Ocean. Protective coatings were not initially specified in the project contract documentation. However, the contractor was unable to achieve the selected cover requirements as well as the class 1 off-shutter finish requirements as stipulated in the project contract (as detailed by SABS 1200), and as a result needed to apply a protective coating to achieve an “effective” cover which met the project requirements.

In-construction photographs shown below:

Figure 28: Cape Town Stadium during Construction 1 (Henry Fagan and Partners, 2015)

Figure 29: Cape Town Stadium during Construction 2 (Herber, 2010)

A cover survey was conducted to assess the extent of the problem.

In order to achieve the class 1 off-shutter finish, the existing concrete surfaces was scarified, cleaned and rebuilt with Sika Monotop-615 HB and Sika Monotop-620. Both materials are single component polymer modified cementitious repair products containing silica fume. They were used in different circumstances depending of the particular local requirement, such as vertical application etc. The Sika Monotop-615HB also contains a Sika Ferrogard corrosion inhibitor.

The cover requirements were met with applying Sikagard-703W, which is a penetrating silane/siloxane blend hydrophobic treatment, thereby applying an effective cover to meet the project requirements.

Highly stringent time constraints limited the choice of solution. The selected strategy had a service-life of 6 years. No future maintenance plan on the coating was decided at the time.

CASE STUDY OF 27 WALE STREET

The project entailed the structural and spalling repairs, waterproofing and painting of the entire façade of the 27 Wale Street government building for the Department of Transport and Public Works.

Figure 30: 27 Wale Street View. Image taken on 09-11-2016.

To repair spalled areas, un-sound concrete was removed and a migrating corrosion inhibitor (Sika FerroGard-903 Plus) was applied. This is a migrating corrosion inhibitor which does not alter the appearance of the concrete surface, which considering the historic status of the building façade was an important consideration.

The ribbed pattern of the façade was reinstated using a Cemflex modified stipple and Sika TopSeal-107 covering an area of 4730m^2. The Sika TopSeal-107 was used to restore the concrete façade appearance and to provide additional protection in order to increase the service-life of the concrete façade. This provided a smooth surface ribbed-like finish. In order to achieve a consistent finish, sample patches were applied in order to keep colour variations to a minimum. A twenty-year guarantee was offered on this protection system to the client.

Figure 31: Close-up view of repaired stipple detail on 27 Wale Street. Image taken on 09-11-2016.

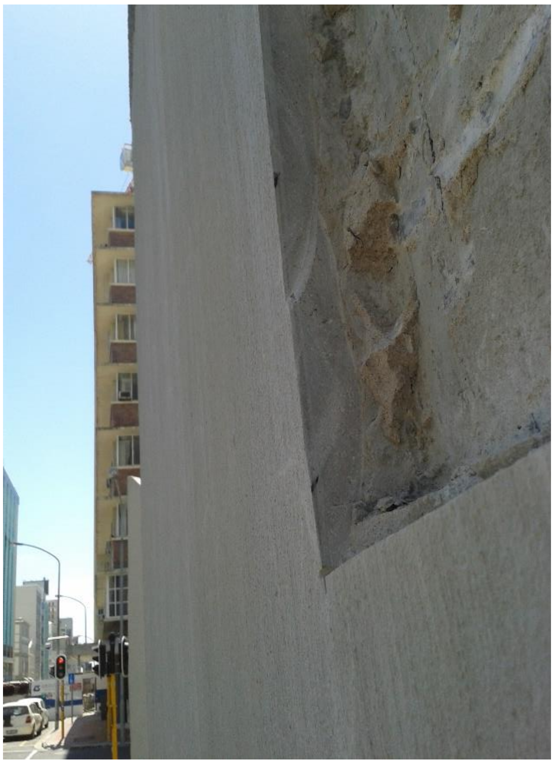


Figure 32: Close-up view of repair profile of 27 Wale Street. Image taken on 09-11-2016.

CASE STUDY OF VICTORIA ROAD BRIDGE REPAIRS, PLUMSTEAD

The project entailed the repair and coating of the Victoria Road bridge over rail in Plumstead Cape Town. Investigations showed that there were many areas of spalling concrete, due to carbonation induced corrosion, which was partly due to low reinforcement cover of some areas.

Figure 33: Completed Repairs of Victoria Road Bridge Plumstead. Image taken on 09-11-2016.

The SikaLastic-152, fibre reinforced polymer modified cementitious coating was selected as the preferred coating option in particular for its crack bridging abilities. The Sikagard-550W Elastic was also considered as an alternative, but was not preferred because the semi-permanently wet concrete substrate was seen as a problem for application of acrylic coatings. This was a particular concern as bridge joints were found to have moisture leakage.

In the site visit on 09 November 2016, it was noted that the flexibility of the material can be felt by pressing one’s nail into the coating – An indentation can be seen for a few seconds and felt.

Figure 34: Close-up view of SikaLastic-152 finish. Image taken on 09-11-2016.

Figure 35: Victoria Road bridge repairs below deck. Image taken on 09-11-2016.

OTHER MAJOR COATING USES

1.2 4 DORP STREET

- Coating used: SikaTop-107 ZA

Figure 36: 4 Dorp Street Front Façade. Image Taken on: 09-11-2016.

1.3 9 DORP STREET

- Coatings Used: SikaTop-107 ZA with a Sikagard-703W overcoat in some areas. The building façade required major repairs with tests indicating chloride levels at reinforcing reaching up to 1.2%. This was partly due to the corrosion of the steel fixing elements of the facade. The façade had been built with thick layers of plaster

Figure 37: 9 Dorp Street Façade. Image Taken on 09-11-2016.

1.4 UCT SPORT CENTRE REPAIRS

- Coating used on façade: SikaTop-107 ZA

Figure 38: UCT Sport Centre Façade (Staticflickr, 2017)

RELATIVE SYSTEM COSTS

A high level indicate cost was calculated for the coating systems listed above, and is presented below. These numbers are not to be used for costing purposes, they are merely shown here to indicate the relative difference in cost between the different systems:

- Sikagard 706 Thixo (silane Cream) – R95/m^2
- Sikagard 703W (silane-siloxane) – R35/m^2
- SikaTop-Seal-107 ZA (PMC) at 2 mm thick – R117/m^2
- SikaLastic-152 at 3 mm thick (PMC) – R193/m^2
- Sikagard-550W Elastic (Acrylic) for 1 primer coat + 2 top coats: R90/m^2

APPENDIX C: PROPERTIES OF COMMON POLYMER-MODIFIED CONTRETE AND MORTAR MIXES

	Uses	Fresh Concrete Properties	Structural Properties	Durability Properties	Limitations
Styrene-Butadiene Latex	Repairs to bridge decks and parking garages, swimming pool coatings, patch repairs, repair of stadiums. Use has decreased since 1950s for more cost-effective systems.	Workability significantly improved. Working time decreased (15 -30 mins after mixing). setting time increased. bond strength increased.	Typically, lower compressive strength (compared using similar cement, aggregate, water content) than OPC concrete.	Reduced permeability. Reduced water absorption. Improved carbonation resistance. Improved chloride resistance. Enhanced freeze-thaw resistance without additional air entrainment.	Sensitive to hot, dry, sunny and windy conditions during curing. May be sensitive to temperatures below 7degC. Not recommended for underwater uses. Suitable for only low-to-moderate chemical exposure.
Acrylic Latex	Repair of industrial and commercial floors subject to abrasion, vibration and aggressive environments, coatings to marine decks (ships), spray-on coatings, basement waterproofing, patch repairs and coatings.		improved adhesion, abrasion, impact strength, flexural strength. Significantly increased tensile strength (increases with density of acrylic used) and therefore improved crack bridging ability.	Improved resistance to permeability. Long-term durability under wet conditions can be obtained. Significant water resistance. Good weathering resistance. Good UV resistance. Significant chloride ion penetration reduction. Good freeze-thaw resistance.	

	Uses	Fresh Concrete Properties	Structural Properties	Durability Properties	Limitations
Epoxy Polymer Modifiers	Used for grouts, stuccos, liners. Also protective coatings, skid-resistant coatings, bridge deck and parking garage overlays.	Increased workability and setting time. Reduced segregation and bleeding.	Compressive strength unchanged. Tensile and flexural strength increased up to 100%. Lower modulus of elasticity. Higher ductility.	Reduced permeability and chloride ion penetration. Good resistance to weathering, moisture, common organic acids and alkalis after curing. Reduced shrinkage. Increased freeze-thaw resistance. Improved salt scaling resistance, acid resistance and wear resistance. Improved chemical resistance.	Only polymerises between 10 - 30degC in highly alkaline environment.
Redispersible Polymer Powders	Can be used for same uses as conventional latexes but with convenience and accuracy of premixing. Mainly used for: Ceramic tile adhesives and grouts, underlayments and industrial floor toppings and concrete repair and patching mortars.	Comparable to latexes of similar composition, except that slightly higher w/c ratios are required for a similar flow	In general, slightly less favourable properties than similar latexes. Some researchers reported similar values to that of conventional latexes using the same polymers.	In general, slightly less favourable properties than similar latexes. Low diffusion to chloride ion, oxygen and carbon dioxide. Low drying shrinkage has been reported.	Not to be used where a high degree of water resistance is required (e.g. bridge decks). When used as patching mortars, may require additives to meet stringent property requirements such as low shrinkage, low permeability to chloride ions and carbon dioxide.

	Uses	Fresh Concrete Properties	Structural Properties	Durability Properties	Limitations
Others	These include: Natural rubber latex, copolymers of butadiene and acrylonitrile, polymers and copolymers of chloroprene, polymers and copolymers of vinyl acetate, copolymers of vinylidene chloride, polymers and copolymers of vinyl esters and alcohol, and bituminous latexes. Use depends on particular type.	Water reduction is obtained with most. Butadiene-acrylonitrile latexes have a greater water-reducing effect than polyvinyl acetate latexes. Most increase setting times, with chloroprene polymers giving the largest increase. Vinyl acetate-ethylene or ethylene-vinyl acetate copolymers gives moderate increase. Entrained air contents are higher than similar unmodified mixtures, unless antifoam agents are used.	Similar performance to conventional PMC's in adhesion, abrasion resistance, and tensile and flexural strengths. However, the degree can vary depending on the type.	Durability may be limited. Copolymers of vinylidene chloride are virtually discontinued as they tend to release chloride ions. Polyvinyl acetate latexes are degraded by hydrolysis in wet, alkaline environments & should not be used in cementitious mixtures that are liable to be exposed to moisture. Most of these polymers reduce water permeability. Marked strength reduction between dry and wet test conditions, but butadiene-acrylonitrile copolymers may be an exception.	

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