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UNIVERSITY OF CAPE TOWN  
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD



# The Influence of Curing Techniques and Chemical Admixtures on the Properties of Concrete

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Prepared by: Michael Martin  
Supervisor: Assoc. Prof. H.D. Beushausen  
Co-Supervisor: Prof. M.G. Alexander

For submission to the Faculty of Engineering and the Built Environment, University of Cape  
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*"It is not difficult to make good concrete. What is difficult is to make consistently good concrete."*

- Dr F S Fulton (Addis, 1986)

## Declaration

This thesis is a presentation of original research work. Every effort was made to clearly indicate, with reference to literature, collaborative research and discussions, the contributions of other researchers. This work has not been previously submitted in any form at another institution for any degree. This thesis is being submitted for the degree of Master of Science in Civil Engineering at the University of Cape Town.

SIGNED: \_\_\_\_\_

Date: \_\_\_\_\_ 30/11/2012

Michael James Martin

University of Cape Town

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## Abstract

The deterioration of concrete in South Africa is becoming of major concern to the construction industry. The maintenance of reinforced concrete structures is an extremely expensive exercise and is a continuing necessity. Concrete curing is a practice that is understood to be a necessity within industry, but is often overlooked as a result of time and/or economic constraints. The objective of the study is to ascertain whether or not the implementation of better quality and alternative curing techniques will improve the durability properties of the concrete.

Curing is defined as the maintenance of appropriate moisture and temperature conditions to permit the continuation of the hydration or pozzolanic reaction. The objective of curing is to ensure the progress of hydration reactions causing the filling and discontinuity of capillary voids by hydrated compounds in newly placed concrete.

Modern curing methods are generally classified as wet or sealing. Wet methods include fogging, sprinkling, ponding, immersion and wet coverings. Sealing methods include plastic coverings and membrane forming curing compounds. Crystallising permeability reducing admixtures may be included in the concrete mix design in order to decrease the penetrability of concrete by decreasing the interconnectivity of the pore structure. Curing methods need to be employed in order to assure specified durability limits are acquired, as durability constraints are implemented in industry.

Various methods of curing were tested in order to establish the effect of the techniques on the durability properties of concrete. Samples were placed in water and in winter (Western Cape, South Africa) and simulated summer environments. Various curing techniques were then employed within each of the exposure environments. The curing methods were damp hessian, cling wrap, two curing compounds and two crystallising permeability reducers (PRA's). Samples were also left untreated in each environment as reference samples. Compressive strength, oxygen permeability, water sorptivity, chloride conductivity, bulk diffusion and accelerated carbonation tests were conducted.

The results obtained in the study concur with those presented in literature. Prolonged periods of moist curing are significantly beneficial to the compressive strength and durability properties of concrete, however, full water immersion is not a feasible alternative for large or insitu-cast concrete elements. Results of the study show that damp hessian was the best method to ensure superior durability properties. The sealing of samples with curing compounds in a cool and wet environment (winter) is not recommended, whereas it is marginally beneficial, as was clingwrap, in a hot and dry environment (summer). The crystallising PRA's provided mixed results and were favourable where excess moisture was available and fairly ineffective in dry conditions. The durability properties of concrete are markedly affected by the curing technique implemented.

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## List of Symbols and Abbreviations

|                   |   |  |
|-------------------|---|--|
| CEM I             | - | Portland Cement  |
| FA                | - | Fly Ash  |
| GGBS              | - | Ground Granulated Blastfurnace Slag                                      |
| CSF               | - | Condensed Silica Fume  |
| C <sub>3</sub> S  | - | Tricalcium Silicate  |
| C <sub>2</sub> S  | - | Dicalcium Silicate   |
| C <sub>3</sub> A  | - | Tricalcium Aluminate   |
| C <sub>4</sub> AF | - | Tetracalcium Aluminoferrite  |
| CSH               | - | Calcium Silicate Hydrate [C <sub>3</sub> S <sub>2</sub> H <sub>3</sub> ] |
| CH                | - | Calcium Hydroxide [Ca(OH) <sub>2</sub> ]                                 |
| H                 | - | Water [H <sub>2</sub> O]   |
| SCM               | - | Supplementary Cementitious Materials                                     |
| PRA               | - | Permeability Reducing Admixture  |
| CC                | - | Curing Compound  |
| ITZ               | - | Interfacial Transition Zone  |
| SANRAL            | - | South African National Roads Agency Limited                              |
| DI                | - | Durability Index   |
| OPI               | - | Oxygen Permeability Index  |
| WSI               | - | Water Sorptivity Index   |
| CCI               | - | Chloride Conductivity Index  |

## CHAPTER ONE

### 1. Introduction

#### 1.1. Background to Study

Deterioration of reinforced concrete is a significant problem throughout South Africa, with a greater number of structures failing to fulfil their required service life without requiring considerable maintenance. Concrete protects the steel reinforcement and prevents corrosion of the steel by forming a passive oxide layer as a result of the alkaline environment. The deterioration of concrete generally comes about as a result of the corrosion of the embedded steel due to the ingress of deleterious substances. Carbonation and chloride ion diffusion are the most common mechanisms resulting in the depassivation of steel reinforcement.

Curing is an exceedingly important part of the construction process and is habitually neglected. Appropriate methods are required in order to preserve the mixing water within the concrete to ensure a high degree of hydration. This is particularly important from a durability perspective as the cover layer of the concrete is particularly affected by initial curing. Curing techniques implemented during the initial curing period are well documented and understood. However, the development of new technologies mean that testing is required in order to understand the relative properties that these products impart on the final concrete product. Moist curing is understood to be the most effective form of curing, relative to sealing and additive methods. Moist curing may involve immersion, ponding, fogging or wet coverings. Sealing methods include plastic coverings or curing compounds. Additives have been included as crystallising permeability reducing admixtures (PRA) added at time of mixing. Each of these methods has their merit, but need to be tested within a South African context.

The South African Durability Index (DI) approach was adopted as a way of providing deemed to satisfy rules, which limit DI values for given environmental classes and selected binder types (Ballim, et al., 2009). This performance based approach measures properties of the concrete relevant to the mechanism of concrete degradation. This is as opposed to a prescriptive approach that specifies limiting values for the concrete mix design. In this study, the DI tests were conducted in order to establish the comparative effect of curing regimes on the DI values. Tests were also conducted on concrete samples containing crystallising PRA's, in order to determine if they can be used as durability enhancers i.e. used in instances where proper curing techniques cannot be provided/performed and these chemicals may be used as an alternative to ensure required DI values.

#### 1.2. Objective of the Study

The objective of the study is to determine the effect of various curing techniques, relative to one another, in order to establish the effect on the durability properties of concrete. Curing techniques can then be considered with respect to the environment that the concrete is to be

exposed to and the binder type to be used. The curing techniques to be studied need to be considered with respect to the ambient weather conditions the samples will be exposed to. This is because each curing method may be beneficial in specific environments. Curing techniques will also be scrutinised as to whether they further enhance the durability of treated concrete.

Curing guidelines in South Africa are vague in the description of curing methods to be implemented as well as the duration of curing required. The results obtained will present further support for the need of specifications for on-site curing practices.

### **1.3. Aims**

The aims of the study are as follows:

- i. Investigate the effects of different curing techniques on the DI values of concrete
- ii. Investigate the effects of the crystallising PRA's on the chloride diffusion and carbonation coefficients of concrete
- iii. Determine the effectiveness of the various curing techniques on the durability properties of concrete considering the exposure conditions of each environment.
- iv. Rank the curing methods in terms of performance based on the results obtained in the compressive strength and DI tests.
- v. Indicate the effectiveness of the curing techniques in summer and winter (Cape Town) curing environments.

### **1.4. Hypothesis**

The implementation of better quality curing techniques will significantly improve the durability properties of the concrete and, hence, prolong the service life. Prolonged periods of moist curing is the best method to ensure superior durability properties.

The use of durability enhancers, crystallising PRA's and curing compounds, will improve the durability properties of concrete in situations where traditional methods cannot be employed.

Curing techniques are best implemented and dependant on the exposure conditions. In the Western Cape, summer provides for hot and dry conditions where curing and protection of concrete is a necessity. Conversely, winter provides for cool and wet conditions and the implementation of certain curing methods can be detrimental to the durability properties of concrete.

## 1.5. Research Significance and Implications

The corrosion of steel reinforcement is the main cause of the deterioration of reinforced concrete structures. The implementation of appropriate curing procedures is acknowledged as an important step in ensuring adequate hydration within the concrete matrix, hence improved durability properties. Investigation into the effects of current methods and newer technologies is required in order to illustrate the importance of implementing curing in practice.

The results obtained from this study will illustrate the effect of the curing compounds and crystallising PRA's on concrete durability relative to current methods. The results will also further emphasise the need for contractors and precast concrete manufacturers to employ efficient curing methods for all concrete produced.

Given that improved curing techniques may provide improved durability properties, it can be concluded that the use of enhanced curing techniques may provide for further economic reductions in the mix designs of concrete. The study will also further promote the implementation of the performance based approach to durability as DI limits are increasingly implemented in projects throughout South Africa.

## 1.6. Dissertation Outline

### *Chapter 1:*

A general introduction and overview of the topic is presented. The significance of curing and the effects on the durability properties of concrete are outlined. The aims and hypothesis of the study are detailed.

### *Chapter 2:*

The literature review will firstly seek to explain curing, its effects on durability and the various techniques currently in use. It will also discuss the transport processes and deleterious processes within concrete that lead to the corrosion of reinforcing steel. The DI testing procedure will also be summarised as well as environmental conditions to be considered and current curing specifications.

### *Chapter 3:*

The experimental methodology discusses the mix designs, curing techniques and testing program employed in order to determine the durability properties of the concrete samples.

*Chapter 4:*

The results are presented with each curing technique compared to one another as well as to reference samples. A discussion then draws on the results obtained.

*Chapter 5:*

Conclusions are made regarding the performance of the curing techniques relative to one another. Curing techniques and binder types can then be suggested for the environmental conditions to be encountered in order to ensure that specified durability limits are reached.

University of Cape Town

## CHAPTER TWO

### 2. Literature Review

The following literature review will attempt to examine the theory behind curing and its effect on concrete hydration and, hence, concrete durability. The correlation between curing and construction techniques and concrete durability properties will be discussed in order to further understand; firstly, the importance of employing proficient curing techniques and, secondly, what possible 'non-standard' alternatives exist to traditional methods

The definition and influences of curing will be discussed in detail. The transport and deterioration mechanisms of concrete will also be examined, followed the various curing techniques that currently are available to the construction industry. A clear understanding of the effects of curing is well documented, however, further evidence is required in order to help develop a keen recognition within the industry through further testing with modern chemicals and within a South African context.

#### 2.1. Curing

The curing of structural concrete has long been an overlooked step in the construction process. Only in the last two decades, with the development of durability requirements, has the importance of curing started to be taken seriously. For many decades concrete durability was associated with increased cement content. (Richardson, 2002) Curing is an essential part of the construction process and significantly beneficial to the hydration process.

##### 2.1.1. Fundamentals of Curing

###### 2.1.1.1. Definition of Curing

Curing is defined as the maintenance of appropriate moisture and temperature conditions to permit the continuation of the hydration or pozzolanic reaction. The reaction rate increases with increasing temperature. (Grieve, 2009) Curing of concrete is essential to ensure that the greatest compressive strength and the highest degree of impermeability are achieved to meet the requirements of service. (Krook, 1995), (Perrie, n.d.) The objective of curing is to ensure the progress of hydration reactions causing the filling and discontinuity of capillary voids by hydrated compounds in newly placed concrete. (Güneyisi, et al., 2007), (Spears, 1983)

###### 2.1.1.2. Curing and Hydration

The relationship between hydration and curing is extremely important in determining how curing techniques influence the final properties of the concrete and for what duration these processes need to be implemented. The hydration process is a chemical reaction that takes place when cement particles react with water to form hydration products. Hydration products

form in the water filled spaces within the concrete matrix and will continue to form until the maximum degree of hydration has been attained or until the water filled space has been completely filled. The degree of hydration may be limited should the concrete dry out rapidly, thus leaving no water in the pores of the concrete to enable continued hydration. (Spears, 1983)

Powers and Brownyard (Taylor, 1997) found, through extensive research, that the limiting w:b ratio needed to ensure 100% hydration was 0.38. Most investigators tend to agree that a lower w:b ratio will inhibit sufficient hydration. It was also found that should a paste having a w:b ratio of less than 0.44 is cured under sealed conditions, self-desiccation will occur and result in gel pores not sufficiently filled and capillary pores being empty, resulting in a lower degree of hydration and increased porosity.

Spears (1983) cites a study performed by Powers (1947) in which stored samples of dry cement were exposed to atmospheres of various RH's for a period of 6 months.

Figure 1 below depicts the mass of water absorbed per gram of cement at various RH's. It can be seen that there is a sudden rise in the curve at about 80%, indicating the effect that a highly humid environment has on the hydration of cement. Variations in the RH of the surrounding atmosphere cause a loss or gain of water available for hydration. (Taylor, 1997) Powers found that the ambient moisture content must be maintained at a relatively high value of greater than 80% to ensure a high degree of hydration.

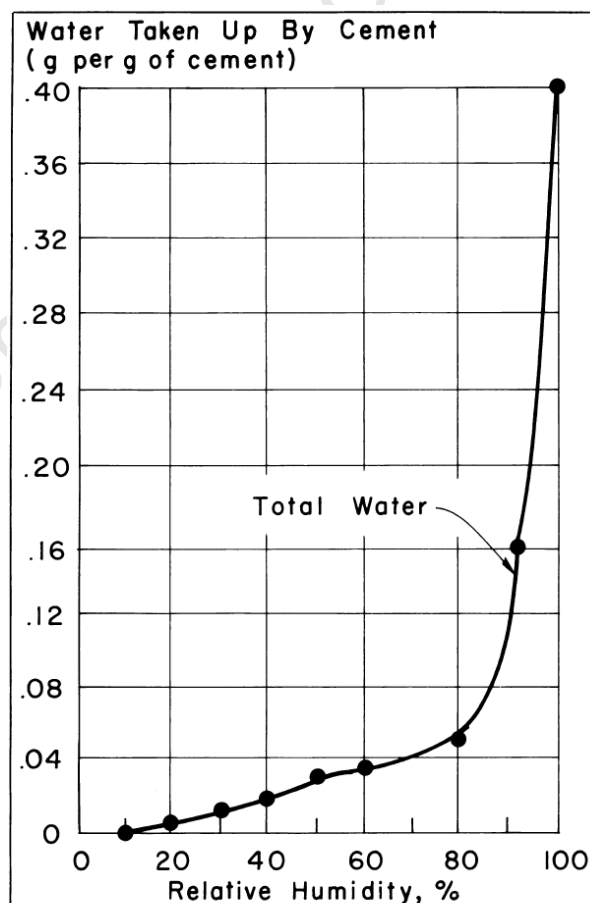


Figure 1: Water absorbed by dry cement exposed to varying RH's (Spears, 1983)

When water is allowed to evaporate from the cover layer of the concrete, this leads to an increased porosity within this cover zone, leading to an increase in penetrability and potential for concrete degradation. Figure 2, below, illustrates the effect of RH on the drying rate of the concrete.

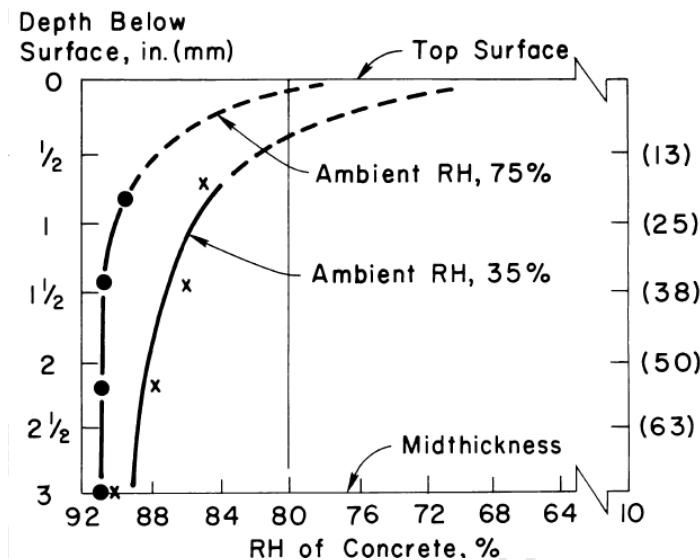


Figure 2: Humidity gradient within 150mm concrete slab (Spears, 1983)

Should the start of curing be delayed, evaporation of pore water from the cover layer halts the hydration process. This will lead to a cessation in the growth of hydration crystals, therefore resulting in increased permeability. Insufficient curing may lead to an increase in the permeability of the concrete cover layer by five to ten times. (Comité Euro-International du Béton, 1997) Early moisture loss from the concrete surface will also lead to plastic settlement and shrinkage, resulting in near surface stresses. (Evans, 2011) This will lead to a propagation of micro-cracks, therefore increasing the interconnectivity between pores. Increased permeability would facilitate the ingress of deleterious agents, leading to the eventual corrosion of steel. (Perrie, n.d.) Evaporation also leads to CH being deposited in the entrances of the capillaries by the evaporating pore water. This CH is then carbonated by  $\text{CO}_2$  in the air, sealing the capillaries and making it very difficult to get water back into the concrete to replace the evaporated water. This also leads to a reduction in the degree of hydration. (Kellerman, 2009)

Low relative humidity, high wind speed and high ambient and concrete temperatures result in rapid evaporation of water from the surface of the concrete. This phenomenon is especially troublesome in elements with large exposed surface areas. (Kellerman, 2009) Alternative options to minimise the effect of the evaporation of the surface pore water will be discussed in Section 2.1.1.2.

### *Rate of Reactions*

The rate at which the hydration and pozzolanic reactions take place are important in determining the minimum duration of curing required. Differing binder types and contents,

materials used and environmental conditions can have significant effects on the rate of hydration and, hence, the curing requirements.

Compressive strength gain of concrete is attributed to the hydration of  $C_3S$  and  $C_2S$ , and as can be seen in Figure 3, the hydration of  $C_3S$  occurs rapidly, peaking at approximately 10 days.

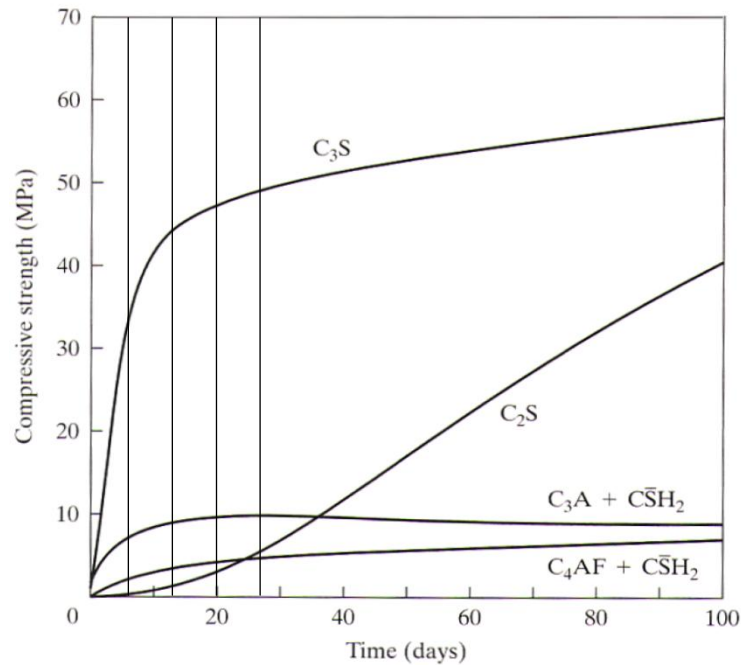


Figure 3: Rates of strength gain of various clinker phases (Kosmatka, et al., 2003)

This is further emphasised by Figure 4, with the rapid rate of CSH formation occurring between 6 hours and 90 days. The formation of CH also occurs over the same period and is important in the reaction of pozzolans and latent hydraulic binders, as will be discussed below.

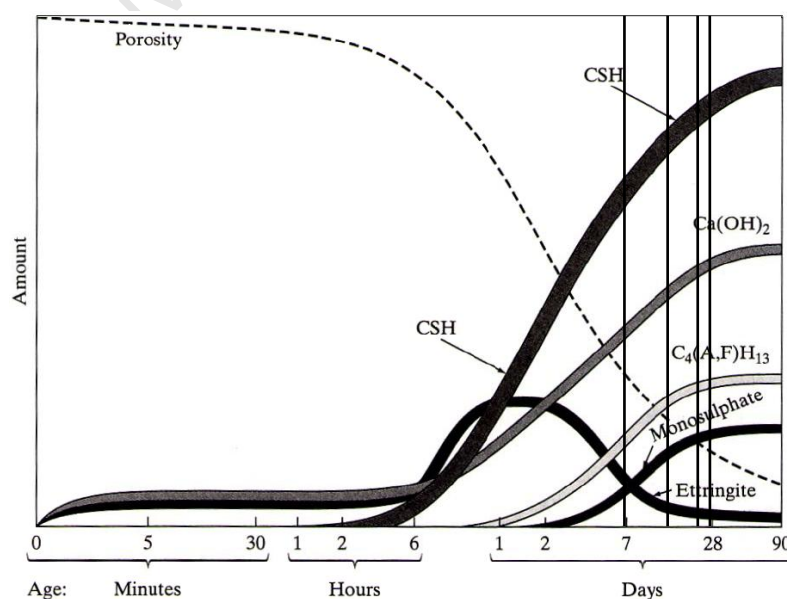


Figure 4: Relative volumes of principal hydration products as a function of time (Kosmatka, et al., 2003)

Table 1 illustrates the effect of FA on the initial and final set of the concretes. One can see that there is a delay in setting times due to a decreased rate of hydration.

*Table 1: Effect of FA on Concrete Setting Time (Kosmatka, et al., 2003)*

| Sample  | Setting Time (hr:min) |       | Retardation Relative to Control (hr:min) |       |
|---------|-----------------------|-------|--|-------|
|         | Initial               | Final | Initial                                  | Final |
| Control | 4:15                  | 5:30  | —  | —     |
| Class C | 4:40                  | 6:15  | 0:30                                     | 0:45  |
| Class F | 4:50                  | 6:45  | 0:35                                     | 1:15  |

SCM's result in a decreased rate of reaction due to the delay of the reactions of the pozzolans and latent hydraulic binders. Pozzolans require CH that has been liberated from the hydration of CEM I in order to form CSH and other concreting compounds and latent hydraulic binders require an alkaline environment in order to form CSH. As the formation of CH and alkaline need to occur before these reactions may occur, there is thus a requirement for prolonged curing.

### 2.1.2. Reasons for Curing

Hydration and pozzolanic reactions can only occur when sufficient water is present for the reaction processes to occur. This requires that the capillaries in the concrete matrix are filled with water and that it is kept within the concrete. Kellerman (2009) discusses that concretes containing a w:b ratio of less than 0.5 require excess water to be provided at the surface. Not only does this provide excess water for hydration, but also prevents water from evaporating from the pore structure. Evaporating water leaves behind CH deposits in the pores, which carbonates when exposed to the atmosphere and can block applied water from getting back into the concrete. Due to this effect, Kellerman (2009) recommends that curing procedures be initiated as soon the concrete is exposed to the environment. This is not the only reason to initiate early curing, but one that can have a more immediate impact.

Spears (1983) lists the following benefits of properly employed curing techniques:

- Proper curing decreases
- Permeability
  - Surface dusting
  - Thermal shock effects
  - Scaling tendency
  - Cracking
- Proper curing increases
- Strength development
  - Abrasion resistance
  - Durability
  - Pozzolanic activity
  - Weatherability

Minimising the drying rate of concrete at the surface layer is extremely important in ensuring sufficient durability properties are ensured in the final product. Understanding the drying rate also helps determine the required period and type of curing required. Exposure to high wind velocities can result in a high evaporation rates. The severity of drying is dependent on four factors: (ACI Committee 306, 2002)

- the temperature of the concrete
- the temperature of the air
- the wind speed
- the relative humidity of the air.

Should the evaporation rate exceed the bleeding rate of the concrete, drying of the surface layer occurs and the probability of plastic-shrinkage cracking increases when the environmental conditions increase evaporation or when the concrete has a reduced bleeding rate. Inevitably, the bleeding rate of the concrete will tend to zero and the surface will dry out. This may then lead to the requirement of additional curing procedures. (ACI Committee 305, 1999)

Bleeding rates of concretes containing SCM's are generally lower than those for plain CEM I cement concretes due to the fine nature of the material decreasing the flow of bleed water. Concretes containing CSF is particularly prone to plastic shrinkage due to bleeding rates of approximately  $0.25 \text{ kg/m}^2/\text{hr}$  (Kosmatka, et al., 2003)

The ACI recommends that precautions should be taken when the rate of evaporation is expected to exceed  $1.0 \text{ kg/m}^2/\text{hr}$ , the Canadian Code recommends  $0.75 \text{ kg/m}^2/\text{hr}$  whereas Australian specifications recommend  $0.5 \text{ kg/m}^2/\text{hr}$  as the value at which precautions should be taken and a value of  $1.0 \text{ kg/m}^2/\text{hr}$  as that value where plastic shrinkage cracking is likely to occur. Kosmatka et al. (2003) also suggest that an evaporation rate of  $1.0 \text{ kg/m}^2/\text{hr}$  requires mandatory precautionary measures.

Literature suggests that concrete bleed rates for common conditions of slab construction will lie in the range of about  $0.5$  to  $1.5 \text{ kg/m}^2/\text{hr}$ . However, Powers conducted tests that presented bleeding rates in the range of  $1.17$  to  $4.05 \text{ kg/m}^2/\text{hr}$ , giving generally higher values throughout the range than put forward above. (Uno, 1998) The higher bleed rates mentioned are not problematic, in terms of negating evaporation rates. It is, however, low bleed rates that are detrimental to the overall durability of the concrete in terms of protection by curing due to evaporation rates that exceed these bleed rates.

Figure 5 below provides a graphical method to determine the rate of water evaporation from the concrete surface. Equation 1 (Uno, 1998) provides a numerical alternative. Results obtained from Equation 1 give comparable results to values obtained from Figure 5. There is also a computer calculator (Snell & Balasubhranian, 2008) available in order to determine evaporation rates and inherent risk associated with the conditions. Notably, wind speeds below  $5 \text{ km/h}$  will never give an evaporation rate above  $1 \text{ kg/m}^2/\text{h}$ . Therefore, simply protecting

curing concrete from prevailing winds on site will significantly reduce the rate of evaporation of the pore water.

$$E = 5([T_c - 18]^{2.5} - r[T_a + 18]^{2.5})(V + 4) \times 10^{-6} \quad - \quad 1$$

- $E$  = evaporation rate (kg/m<sup>2</sup>/h)  
 $T_c$  = concrete temperature (°C)  
 $T_a$  = air temperature (°C)  
 $r$  = relative humidity (percent/100)  
 $V$  = wind velocity (km/h)

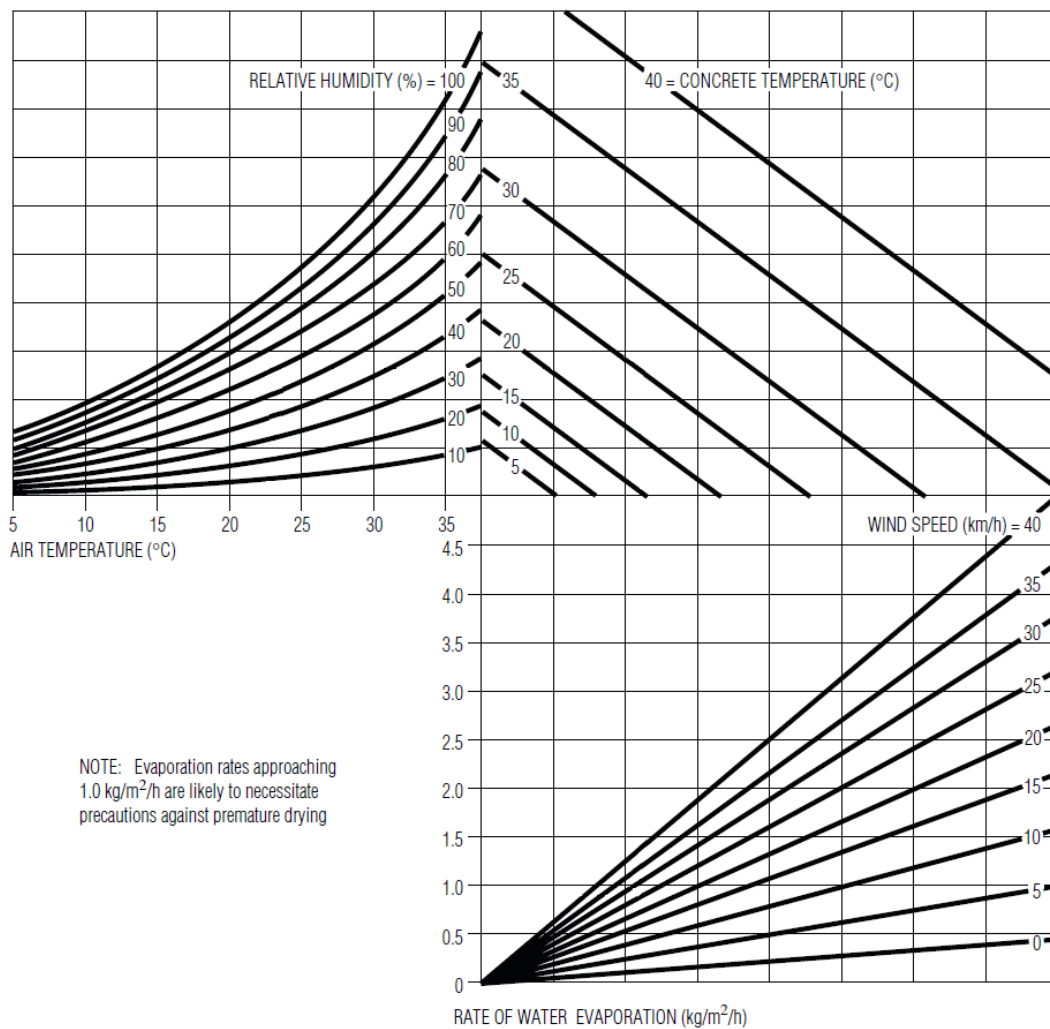


Figure 5: Graphical method for the determination of rate of evaporation from concrete surface (Cement, Concrete & Aggregates Australia, 2004)

### 2.1.3. Curing Techniques

Several curing techniques exist and are used in practice today. They are usually categorised as two generalised methods: (Kosmatka, et al., 2003)

- i. Wet curing methods: Whereby the mixing water is maintained within the concrete, for a specified duration, by immersing or covering the concrete in water or with wet coverings.
- ii. Sealing methods: Reduce the loss of mixing water from the surface of the concrete.

The duration of curing required to achieve the specified durability depends on the chemical composition of the cementitious materials, w:b ratio, mixture proportions, aggregate characteristics, chemical and mineral admixtures, the temperature of the concrete and the effectiveness of the curing method in retaining moisture in the concrete. The high number of factors that influence the durability properties of the concrete result in difficulty in specifying exact curing periods. However, each curing technique has an associated recommended curing period that will be discussed further below. Certain cement and admixture combinations, and high temperature are likely to reduce the time required whereas other combinations of materials, cooler concrete temperatures, or both, will extend the time required. (ACI Committee 308, 2001)

In practice, limited if any attention is paid to curing concrete. The inclusion of curing as a separate pay item in the bill of quantities could contribute to an increased awareness of the importance of curing and encourage good curing practice. (Kellerman, 2009)

#### **2.1.3.1. Wet Curing**

Wet curing methods include ponding or immersion, spraying or fogging and saturated wet coverings. These methods afford some cooling through evaporation, which is beneficial in hot weather. As mentioned above, wet curing is done in order to maintain the presence of the mixing water within the concrete to ensure a prolonged and higher degree of hydration. (Kosmatka, et al., 2003)

##### *Fogging and Sprinkling*

Fogging, illustrated in Figure 6, and sprinkling with water are excellent methods of curing in high ambient temperatures and low humidity's.

Fogging, is applied regularly using a fine mist in order to raise the RH of the air over the concrete, thus decreasing the rate of evaporation from the surface layer.



*Figure 6: Fogging of newly placed concrete*

*(<http://www.iri.ku.edu/projects/concrete/fogging08.JPG>)*

A decrease in the rate of evaporation will minimize plastic shrinkage cracking and allow for a higher degree of hydration.

Sprinkling, as a technique, acts in much the same way as fogging, except that water is more likely to collect on the surface of the concrete and 'seal' it off as well as provide additional water should it be required for the hydration of the surface layer. Krook (1995) found that periodic wetting negatively affected the durability, Oxygen Permeability Index (OPI) and Water Sorptivity Index (WSI) values, of tested samples when compared to wet, retained formwork, plastic sheets and damp hessian curing techniques. It did improve the OPI value of the concrete in question when compared to the curing compound treated sample.

In many instances, these techniques may be used in conjunction with each other. Fogging would be used initially and, once the concrete has set sufficiently to prevent water erosion, sprinkling may be used. Wet coverings; hessian, burlap or sand; may also be used instead of sprinkling. If sprinkling is done at intervals, the concrete must be prevented from drying between applications otherwise alternate cycles of wetting and drying can cause surface crazing or cracking. (Kosmatka, et al., 2003)

### *Ponding and Immersion*

Ponding is ideally used on large flat concrete surfaces, see Figure 7. Earth or sand is placed around the perimeter of the concrete surface can to retain water. Ponding is an ideal method for preventing loss of moisture from the concrete; it is also effective for maintaining a uniform temperature in the concrete.



*Figure 7: Ponding of water on flat concrete slab*

(<http://civil-online2010.blogspot.com/2010/02/curing.html>)

Ponding is considerably labour intensive and is only used in small jobs. Immersion is more common, especially in the laboratory. It is less practical in industry due to the size of tanks that would be required for complete immersion. (Kosmatka, et al., 2003)

#### *Wet Coverings*

Fabric coverings saturated with water, such as burlap, cotton mats, rugs, or other moisture-retaining fabrics, are commonly used for curing, illustrated in Figure 8. Wet coverings should be placed as soon as the concrete has hardened sufficiently to prevent surface damage. Care should be taken to cover the entire surface with wet fabric, including the edges of slabs. The coverings should be kept continuously moist so that a film of water remains on the concrete surface throughout the curing period. Wet coverings of earth, sand, hay, straw or sawdust are effective for curing, but care must be taken to ensure that these materials do not cause discolouration. (Kosmatka, et al., 2003)

Krook (1995) and De Lacy (2008) both found that hessian cured samples exhibited significantly improved Durability Index (DI) values compared to uncured concrete samples. It was also found that the hessian cured samples achieved negligibly poorer results when compared to the wet cured samples.



Figure 8: Hessian cured concrete slab

[http://yourabode.blogspot.com/2009/05/building-eco-friendly-way-concrete-slab\\_19.html](http://yourabode.blogspot.com/2009/05/building-eco-friendly-way-concrete-slab_19.html)

Figure 9 illustrates results obtained by Shafiq et al. (2004). Two sets of samples were exposed to different curing conditions for 28 days. One set was exposed to fogging and the other was dry cured at 65% RH and 20°C. The samples were then exposed to four different environments with varied RH. The results obtained show that the wet cured samples obtained decreased permeability values across the binder types compared to the dry cured samples and exposure to environments of higher RH, post initial curing, results in further decreases in permeability.

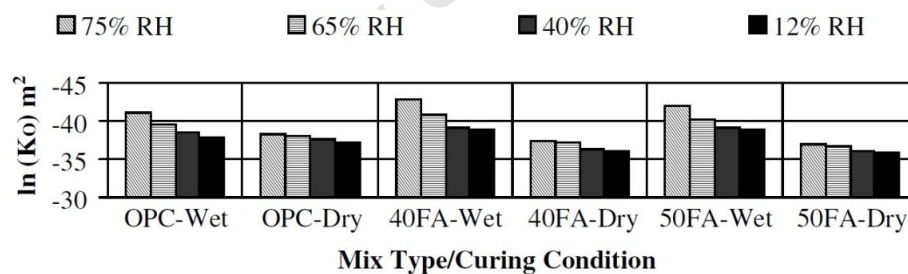


Figure 9: Oxygen permeability of wet and dry cured concrete samples (Shafiq & Cabrera, 2004)

Figure 10 shows the improvement in the compressive strength of samples exposed to prolonged periods of moist curing. There is no difference in the early age compressive strength at 7 days for the samples that were moist cured, but a major difference between the moist cured samples and the air cured samples. This is of significant relevance to industry, as early age compressive strength is important in determining the stripping time of precast elements, as well as for the removal of temporary support for cast in-situ load bearing structures. It can then be seen that compressive strength improves drastically with extended periods of moist curing over time.

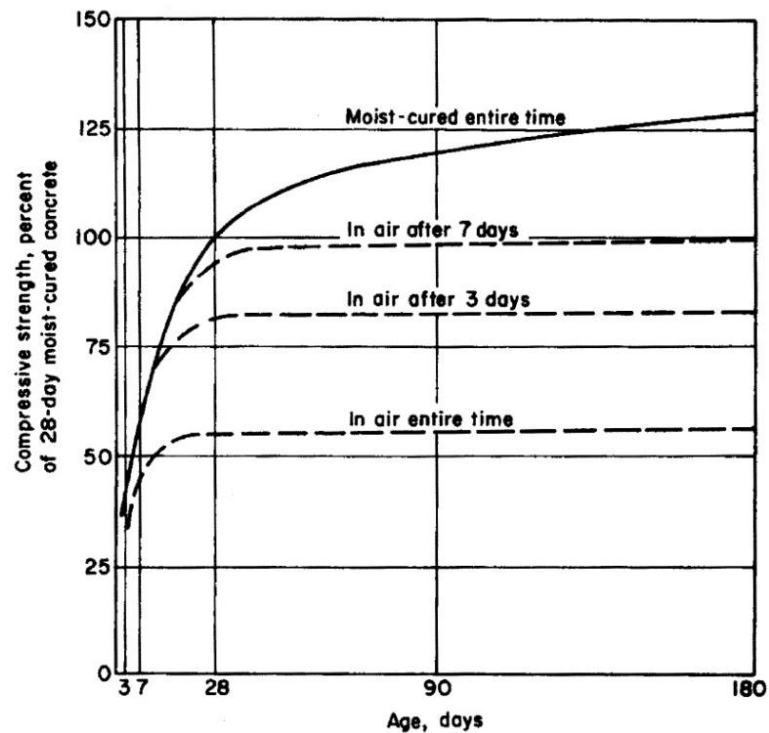


Figure 10: Compressive strength of concrete exposed to varied durations of moist curing (ACI Committee 308, 2001)

### 2.1.3.2. Sealing Methods

#### *Plastic Sheets*

Plastic sheeting materials have been used to act as a means of sealing concrete, Figure 11 and Figure 12, to aid in curing. The sheeting acts to prevent the evaporation of water from the cover layer of the concrete.



Figure 11: Plastic sheeting acts as an effective sealing method

(<http://www.flickr.com/photos/lccstars/6173352010/sizes/l/in/photostream>)



*Figure 12: Cling wrap acts as an effective sealing method*

(<http://www.flickr.com/photos/cybergabi/5526330117/sizes/z/in/photostream/>)

Kellerman (2009) suggests that plastic sheeting be used in the following contexts: floor slabs; tops of beams and columns; and for concrete columns, beams, walls in hot dry conditions. This method eliminates the labour-intensive need for continuous watering of wet covering materials. Plastic sheeting may also be placed over wet hessian or other wet coverings to reduce the rate of evaporation of the water. (Kosmatka, et al., 2003)

ACI Committee 308 (2001) provides a noteworthy example of the varying temperature variations experienced by differing colours of plastic sheeting. Something seemingly trivial can result in a temperature difference of up to 15°C between the black and white plastic sheeting.

In lower ambient temperatures, black plastic may be advisable as it may help in absorbing any ambient heat and prevent any adverse heat loss. Any loss of heat from the concrete can delay the rate of hydration, slowing the rate at which the concrete properties develop. Whereas in higher ambient temperatures, white plastic will aid in reflecting the heat and prevent evaporation of pore water from the surface of the concrete. (ACI Committee 308, 2001)

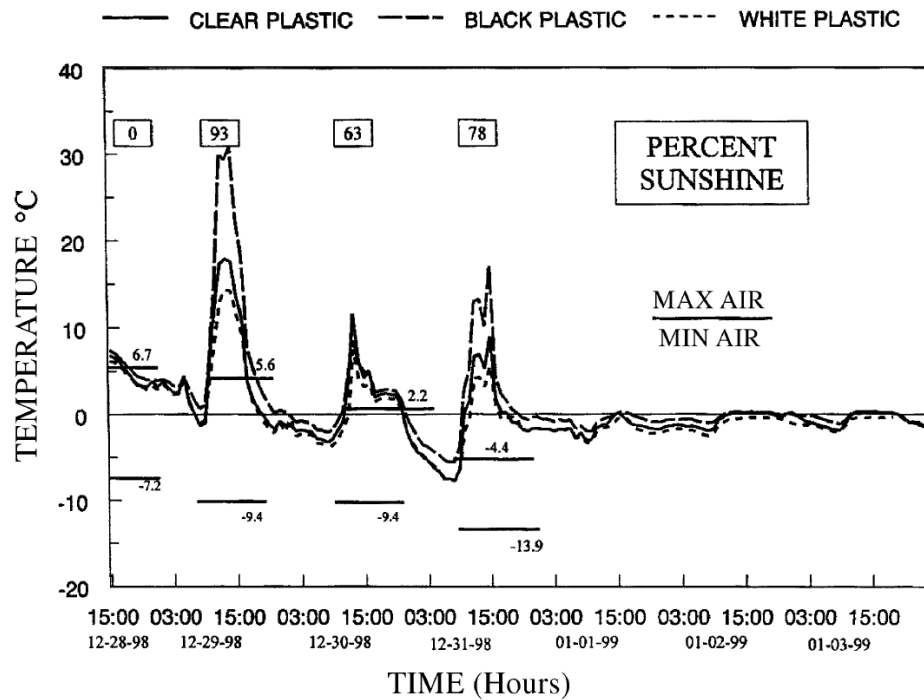


Figure 13: Temperature variations under clear, black and white plastic (ACI Committee 308, 2001)

#### Membrane Forming Curing Compounds

Membrane-forming curing compounds are liquids applied to the surface of the concrete to inhibit the evaporation of water from the concrete. They are applied to the surface layer of the concrete, Figure 14, as soon as bleeding has come to an end.



Figure 14: Application of Membrane-Forming Curing Compound (<http://www.planete-tp.com/en/concrete-curing-a249.html>)

Liquid membrane-forming compounds consisting of waxes, resins, chlorinated rubber, and other materials that can be used to retard or reduce evaporation of moisture from concrete. They are the most widely used method for curing. However, the most effective methods of curing concrete are wet coverings or water spraying that keeps the concrete continually damp. (Kosmatka, et al., 2003) The choice of curing compound is especially important when the concrete is to receive further treatment such as plastering or painting. Some compounds will prevent subsequently applied materials from adhering. (Kellerman, 2009)

Figure 15 illustrates the effectiveness of curing compounds in maintaining a high RH in the concrete matrix, resulting in improved hydration and a decrease in the interconnectivity of pores.

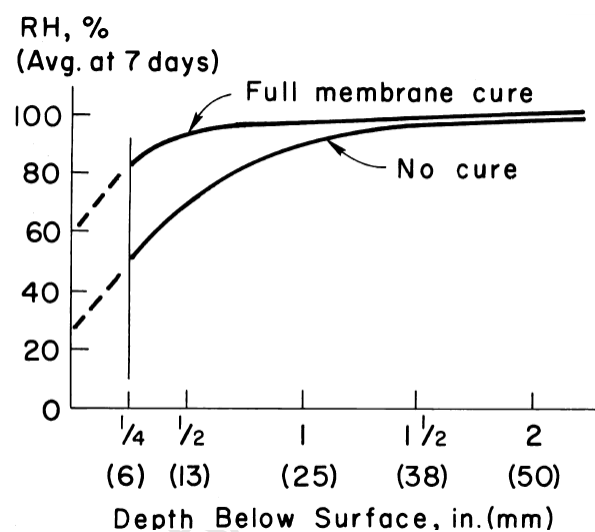


Figure 15: Moisture distribution comparing membrane cured and non cured samples at various depth increments (Spears, 1983)

Figure 15 illustrates that the RH within the concrete may be kept at a high level. Krook (1995) found that the use of curing compounds, Figure 16, was less effective than plastic sheeting and various forms of wet curing. The plastic sheeting may form a better seal and inhibit the loss of pore water due to evaporation.

Complete coverage of the surface must be attained because even small pinholes in the membrane will increase the evaporation of moisture from the concrete. Curing compound manufacturers should be consulted to determine if their product is suitable for the intended application. They should form a tough film to withstand early construction traffic without damage and have good moisture retention properties. (Kosmatka, et al., 2003)

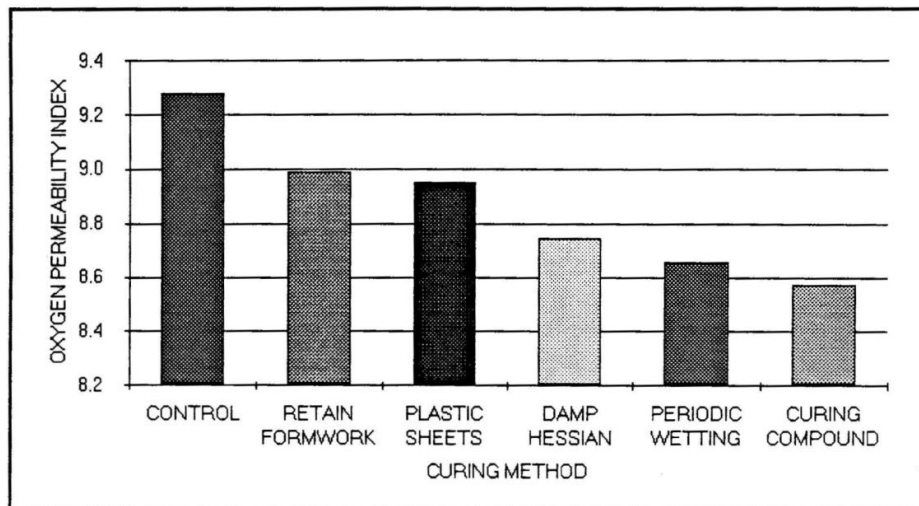


Figure 16: OPI results for comparison of curing methods (Krook, 1995)

### 2.1.3.3. Crystalline Permeability Reducing Admixtures

The use of crystalline permeability reducing admixtures (PRA) is still a relatively young technology in South Africa and as such is still viewed with uncertainty amongst those in the industry.

Crystalline PRA's consist of Portland cement, very fine treated silica sand and various proprietary chemicals. They are hydrophilic in nature and hydrate with water and cement particles in the concrete to form CSH and pore-blocking precipitates in the existing pore structure and capillary voids.

A summary of the general reaction is represented in Equation 2 (ACI Committee 212, 2010):

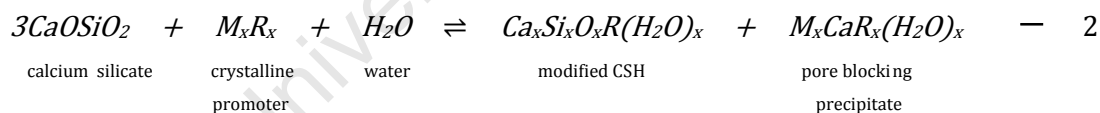


Figure 17 illustrates the hydration of the of the siliceous PRA material over time.

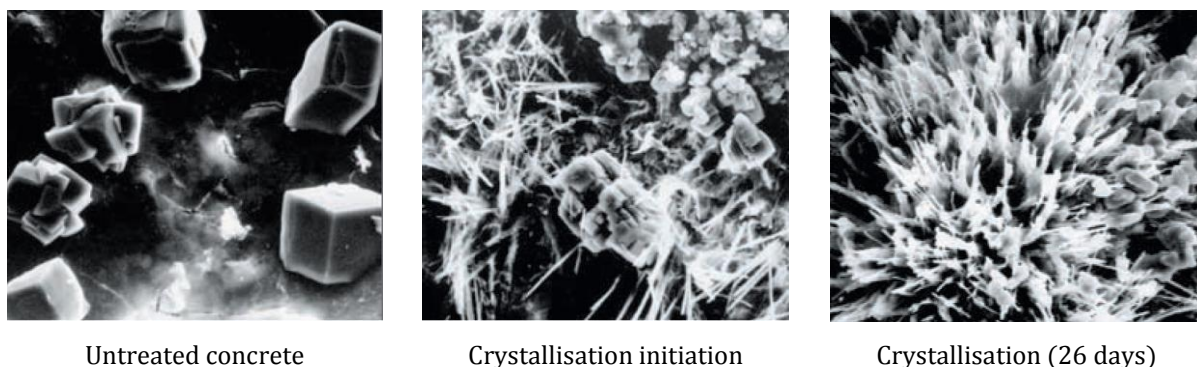


Figure 17: Crystallisation of PRA's (5000x magnification)  
<http://www.PRA1.com/brochures/PRA1%20Technology.pdf>

These crystalline deposits develop throughout the depth of the concrete and become integrally bound within the concrete mass. Crystalline PRA's are said to possess a "self-healing" property. That is, as hairline cracks form over the life of concrete, they are sealed as the continued presence of the crystalline PRA's in the cement matrix activate in the presence of moisture and seal additional gaps. The mechanism is equivalent to the formation of CSH and the resulting crystalline precipitates become integrally bound within the hydrated paste. The resulting concrete is said to significantly increased resistance to hydrostatic pressures. (ACI Committee 212, 2010)

An example of the increase of impermeability of the treated concrete is illustrated, below, in Figure 18 and Figure 19. The use of the crystallising PRA's result in an approximately 70 and 55% decrease in permeability for the 20 and 30% FA replacement concretes respectively. Tests also conducted in this study compared a control concrete with one incorporating crystalline PRA's and found a 70% reduction in permeability for the one incorporating the PRA. (ACI Committee 212, 2010)

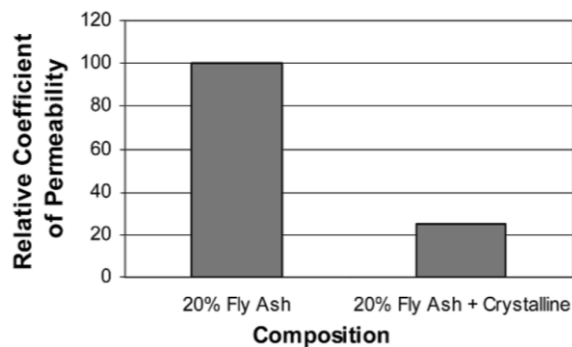


Figure 18: Permeability of concrete containing 20% Type F FA and crystalline admixture (ACI Committee 212, 2010)

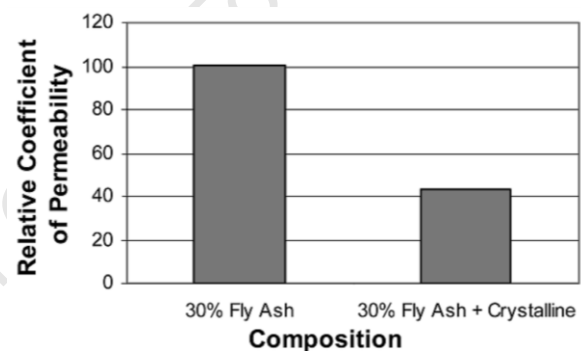


Figure 19: Permeability of concrete containing 30% Type F FA and crystalline admixture (ACI Committee 212, 2010)

Dao et al. (2010) found that the inclusion of an admixture characterized by crystallization activity seemed to have almost no detectable effects. Tests conducted by Munn et al. (2003) found that the inclusion of crystallising PRA's marginally improved the compressive strength, chloride ion penetration and shrinkage properties of the samples, however, not significantly.

Crystalline PRA's can be included in any concrete mix design. Usage of these admixtures is usually, however, limited to structures that will be exposed to moisture, generally in the marine environment or under hydrostatic pressures.

#### 2.1.4. Duration of Curing

Since all the desirable properties of concrete are improved by curing, the curing period should be as long as necessary. (Kosmatka, et al., 2003)

However, modern construction practise necessitates formwork to be removed and concrete elements or structures made accessible as soon as possible in order for the next step in the construction process to continue without hindrance or delay. This often leads to inadequate, if not negligible, curing of concrete.

The duration of curing cannot be stipulated in general terms as there are several variables in play in each and every casting situation. ACI 308R-01 (2001) states the required duration is dependent on:

- the composition and proportions of the concrete mixture;
- the values to be achieved for desired concrete properties;
- the rate at which desired properties are developing while curing measures are in place;
- and the rates at which those properties will develop after curing measures are terminated.

The duration of curing is sensitive to the w:b ratio of the pastes. A lower w:b ratio results in closer initial spacing of the cement particles, requiring less hydration to fill inter-particle spaces with hydration products, as illustrated below by Figure 20. The effect of the period of moist curing is also illustrated for each of the w:b ratios.

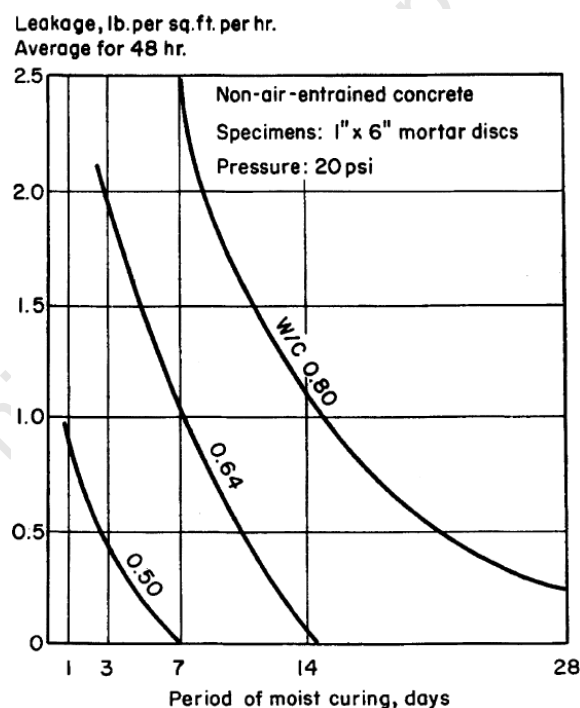


Figure 20: Influence of Curing on Water Permeability of Mortar Specimens (ACI Committee 308, 2001)

The use of SCM's influences the degree of hydration of the cement paste, as well as being influenced itself by water curing processes. Termkhajornkit et al. (2006) conducted a study in order to determine the effect of varying FA contents under varying periods of water curing. It was found that increased periods of water curing resulted in generally improved compressive

strength, Figure 21, and an improved degree of hydration, Figure 22. An important point to note is that the hydration of the FA continues well after the supplied water has been removed. This shows that the pozzolanic reaction continues to occur with the available CH and small amount of water left in the hardened cement matrix.

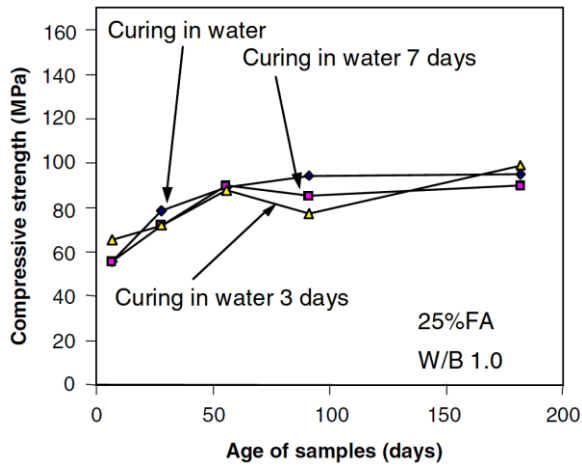


Figure 21: Effect of curing condition on the compressive strength of FA cement paste (Termkhajornkit, et al., 2006)

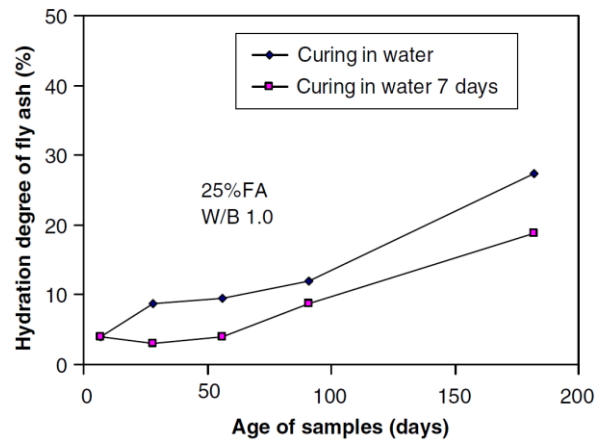


Figure 22: Effect of curing condition on degree of hydration of FA (Termkhajornkit, et al., 2006)

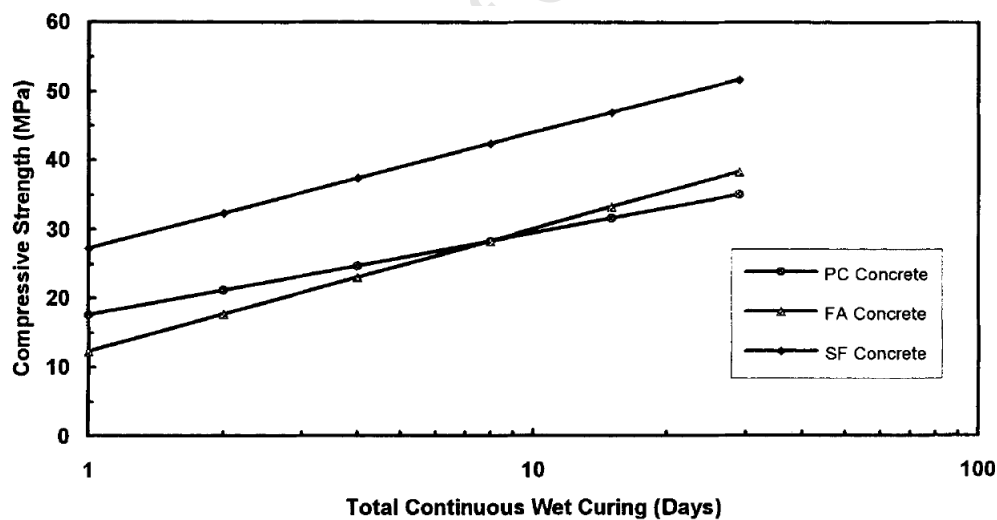


Figure 23: Comparison of Compressive Strength Development in concretes containing various binder types (Khan & Ayers, 1995)

A study by Khan et al. (1995) correlated compressive strength values obtained against duration of water curing, Figure 23, in order to obtain the minimum required length of curing to attain 70% of the 28 day strength compressive strength. The minimum duration calculated is given in Table 2.

*Table 2: Minimum Duration of Curing (Khan & Ayers, 1995)*

| Mix Designation | Minimum length of curing (days) |
|-----------------|---------------------------------|
| PC              | 3.73                            |
| FA-15           | 6.40                            |
| SF-5            | 3.04                            |
| SF-10           | 2.90                            |
| SF-15           | 3.33                            |

As mentioned above, the duration of curing cannot be simply specified. Ideally, curing of concrete should be continued until the properties of the concrete have developed to the required degree. Unfortunately, there are as yet no simple, immediate in-situ tests to determine whether the required characteristics have been met. Table 3 suggests minimum moist curing periods for concrete, but does not differentiate between various cement types. Table 4, however, does discern between cement types. Drawing on the information provided in both tables, it can be seen that in most cases, at least 7 days of curing is required.

*Table 3: Suggested minimum moist curing periods (Kellerman, 2009)*

| Weather   | Minimum moist curing period, days |
|---|-----------------------------------|
| Normal: 18 to 22°C<br>65% RH<br>Low wind speeds | 5                                 |
| Hot: With drying winds                          | 7                                 |
| Cold: 5 to 12°C                                 | 9                                 |

*Table 4: Recommended Minimum Duration of Moist Curing for Concrete (ACI Committee 308, 2001)*

|  | Minimum curing period      |
|--|----------------------------|
| ASTM C 150 Type I  | 7 days                     |
| ASTM C 150 Type II   | 10 days                    |
| ASTM C 150 Type III or when accelerators are used to achieve results demonstrated by test to be comparable to those achieved using ASTM C 150 Type III cement    | 3 days                     |
| ASTM C 150 Type IV or Type V cement  | 14 days                    |
| Blended cement, combinations of cement and other cementitious materials of various types in various proportions in accordance with ASTM C 595, C 845, and C 1157 | Variable. See section 2.9. |

\*with various cement types when no testing is performed and no concrete properties are specified

## 2.2. Methods used to produce durable concrete

In the past, a prescriptive based design approach was taken when specifying mix designs for concrete structures. Modern professionals have started to move away from this approach towards a performance-based design. This has been to accommodate stricter durability specifications required by private developers and government agencies.

Traditionally, improved durability has been associated with decreased w:b ratios, as has improved compressive strength. (Grieve, 2009) It is the significance of concrete strength and stiffness in structural design that has led to the use of these properties as the means for specifying and controlling concrete durability. While there are broad correlations between concrete strength and its other properties including durability, strength should not be used as a determining factor for durability. Numerous examples exist of concrete structures of sufficient strength that are deteriorating prematurely. This is due to several factors; inadequate curing, compaction and mix designs and, partly, because less cement is required in modern structures to obtain the required strength due to modern cement manufacturing advancements, giving rise to higher w:b ratios. This has resulted in structures becoming more penetrable and thus more sensitive to deleterious substances. Modern approaches to durability allow it to be controlled directly through ensuring that the concrete properties meet criteria that give reasonable assurance of adequate service life. These properties can no longer be allowed to be simply related to strength. (Ballim, et al., 2009)

Modern methods in producing durable concrete include concrete mix design and various curing methods. Improved understanding and methods of concrete mix design have significantly improved the quality of concrete produced. Mix designs make use of improved material consumption in order to ensure that the penetrability of concrete is kept to a minimum. Curing methods are employed on site and in precast yards. The various curing methods will be discussed in detail.

## 2.3. Factors influencing Concrete Durability

There are several factors that influence the durability properties of concrete throughout the service life of the concrete. Ballim et al (2009) present the following diagram, Figure 24, as a guide to the differing factors that affect durability.

Each of the factors mentioned, Figure 24, are significant factors that contribute to the durability of the concrete. The scope of the study will focus mainly on the extrinsic influence of curing techniques. However, intrinsic factors and chemical attack, specifically carbonation and chloride penetration, will be discussed. Each of the factors discussed below will be looked at from the perspective of how penetrability is influenced.

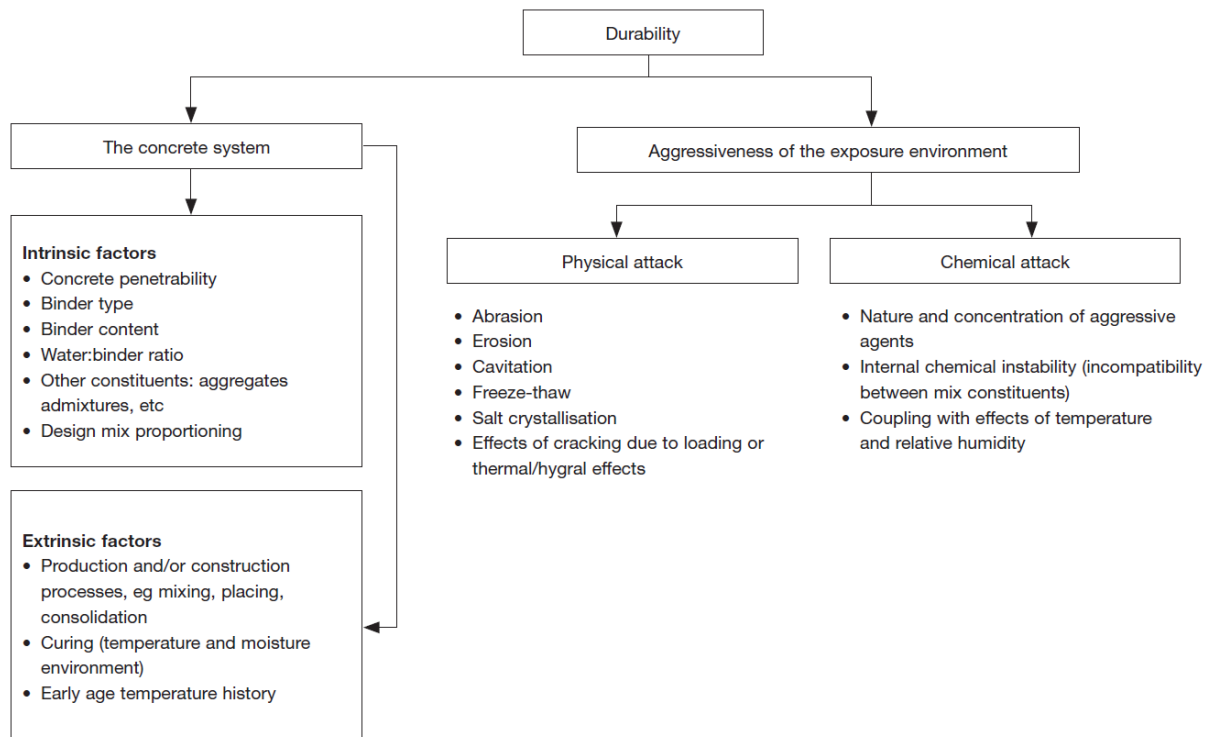
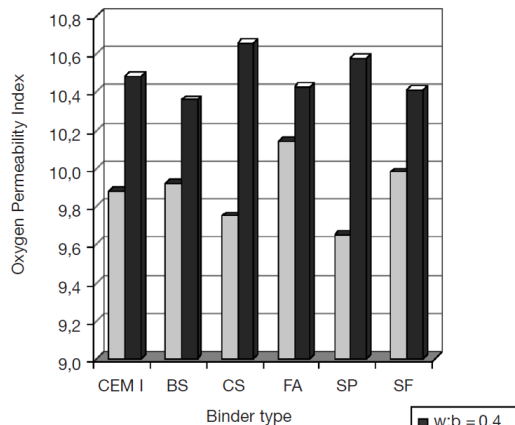


Figure 24: Factors influencing concrete durability (Ballim, et al., 2009)

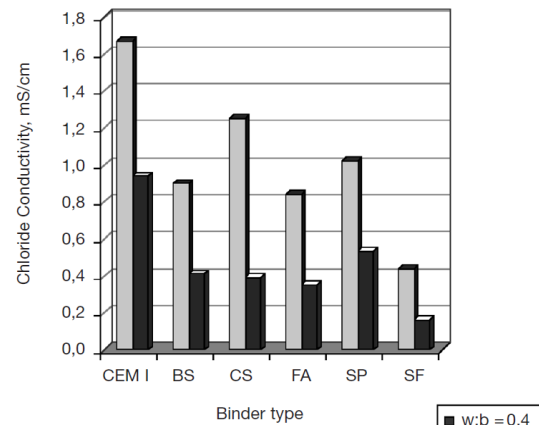
### 2.3.1. Binder Type

Portland cement (PC) is required in all concreting applications. However, there are an increasing number of supplementary cementitious materials (SCM) available that can be used in conjunction with PC. The use of certain binders if correctly proportioned can offer some enhancement to the microstructure, both through their chemical and physical influences on its development. These are physically and chemically different to PC and there is therefore potential for manipulating their combinations to achieve optimum chloride binding capacity and refinement of the microstructure. The quality of the concrete microstructure is influenced both by the quantity and type of binder used and the amount of water in the mix. Recent developments have also seen the introduction of mix proportioning techniques, which are aimed at physically minimising the void space of concrete prior to concrete production. (Dhir & McCarthy, 2011)

Figure 25-28 illustrate the benefits that different proportions of SCM's can impart on the durability properties of concrete elements.

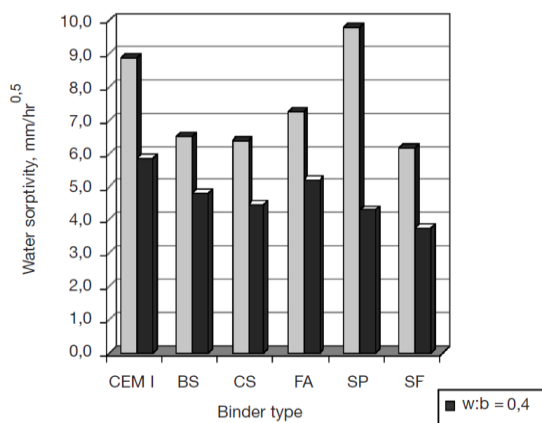


CEM I = 100% PC  
 BS = 50% CEM I / 50% GGBS  
 CS = 50% CEM I / 50% GGCS  
 FA = 70% CEM I / 30% FA  
 SP = 85% CEM I / 15% Superpozz (FA)  
 SF = 93% CEM I / 7% CSF



CEM I = 100% PC  
 BS = 50% CEM I / 50% GGBS  
 CS = 50% CEM I / 50% GGCS  
 FA = 70% CEM I / 30% FA  
 SP = 85% CEM I / 15% Superpozz (FA)  
 SF = 93% CEM I / 7% CSF

Figure 25: OPI Results for varying binder types and *w:b* ratios. (Ballim, et al., 2009)      Figure 26: CCI Results for varying binder types and *w:b* ratios. (Ballim, et al., 2009)



CEM I = 100% PC  
 BS = 50% CEM I / 50% GGBS  
 CS = 50% CEM I / 50% GGCS  
 FA = 70% CEM I / 30% FA  
 SP = 85% CEM I / 15% Superpozz (FA)  
 SF = 93% CEM I / 7% CSF

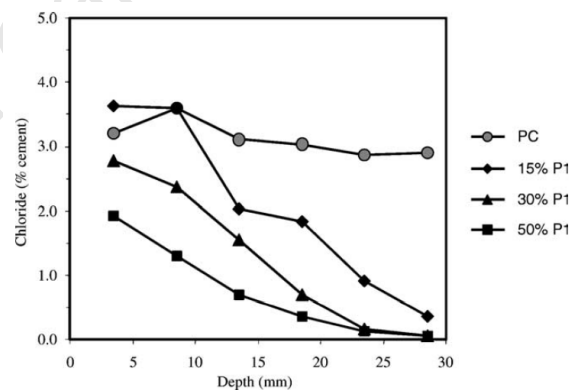


Figure 27: WSI Results for varying binder types and *w:b* ratios. (Ballim, et al., 2009)      Figure 28: Effect of PFA on chloride profiles at 10 years (Thomas & Matthews, 2004)

Table 5 lists the various advantages and disadvantages of the various SCM's available to industry today. There are several advantages to using SCM's in the right proportions and in certain environments.

Table 5: Effects of FA on Concrete (Grieve, 2009), (Addis, B J, 1986)

| SCM  | Advantages  | Disadvantages  |
|------|---|--|
| FA   | <ul style="list-style-type: none"> <li>- Improved workability</li> <li>- Increased later age strength</li> <li>- Reduction in water demand</li> <li>- Reduces permeability</li> <li>- Refines pore structure</li> <li>- Reduced water penetration</li> <li>- Improved resistance to chemical attack</li> <li>- Reduction in shrinkage</li> <li>- Reduced heat of hydration</li> <li>- Reduced tendency to crack</li> <li>- Chloride binding capacity</li> <li>- Reduces probability of ASR</li> <li>- Improves sulphate resistance</li> </ul> | <ul style="list-style-type: none"> <li>- Longer curing requirements</li> <li>- Reduced early age strength</li> </ul>                                 |
| GGBS | <ul style="list-style-type: none"> <li>- Marginally improved workability</li> <li>- Increased later age strength</li> <li>- Reduces permeability</li> <li>- Refines pore structure</li> <li>- Reduces probability of ASR</li> <li>- Improves sulphate resistance</li> <li>- Chloride binding capacity</li> <li>- Reduced heat of hydration</li> </ul>   | <ul style="list-style-type: none"> <li>- Retards setting</li> <li>- Reduced strength development</li> <li>- Increases rate of carbonation</li> </ul> |
| CSF  | <ul style="list-style-type: none"> <li>- Increases cohesiveness</li> <li>- Reduces bleeding</li> <li>- Increases strength</li> <li>- Reduces permeability</li> </ul>  | <ul style="list-style-type: none"> <li>- Reduces workability</li> </ul>  |

### 2.3.2. Binder Content

Research is increasingly showing that the w:b ratio is generally more important than the binder content, which may need to be considered for the specific case. (Ballim, et al., 2009)

Dhir et al. (1996) found that a reduction in binder content, for PC and FA blended concretes, results in an increase in the diffusion coefficients of chlorides into the concretes, Figure 29. The use of a minimum binder content may not ensure durability and it has been shown that equal durability can be achieved with the different binder types, with different contents. There is a need to develop methods to enable direct, explicit design for durability (Dhir, et al., 1996).

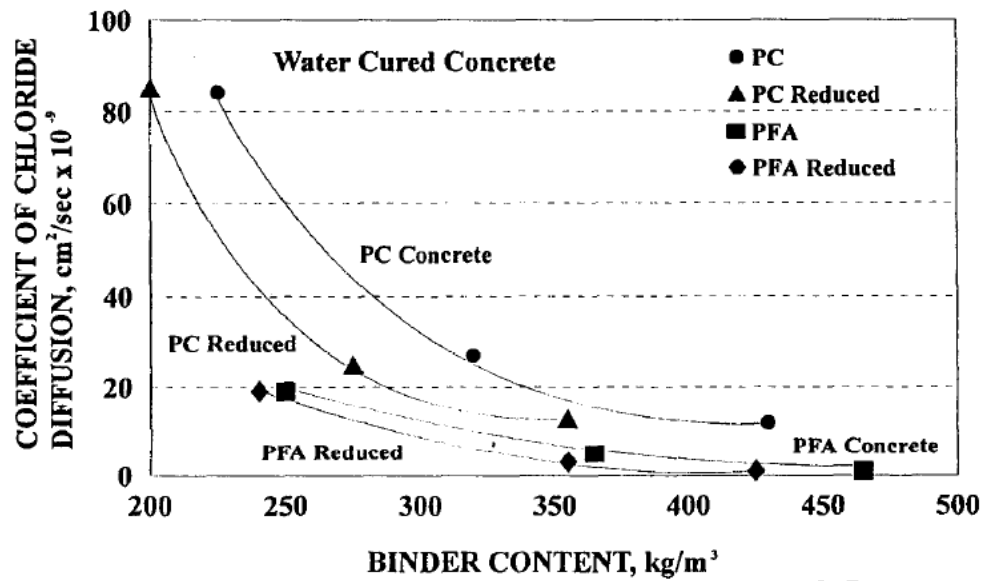


Figure 29: Relationship between chloride diffusion coefficient and binder content of CEM I and FA concrete (Dhir, et al., 1996)

Similar results obtained by Yiğiter, et al. (2007), presented in Figure 30, also show that decreasing cement content leads to an increase in the chloride penetration depth. The PC cement was a CEM I 42.5N and the SC a CEM III/A 42.5N. (Yiğiter, et al., 2007)

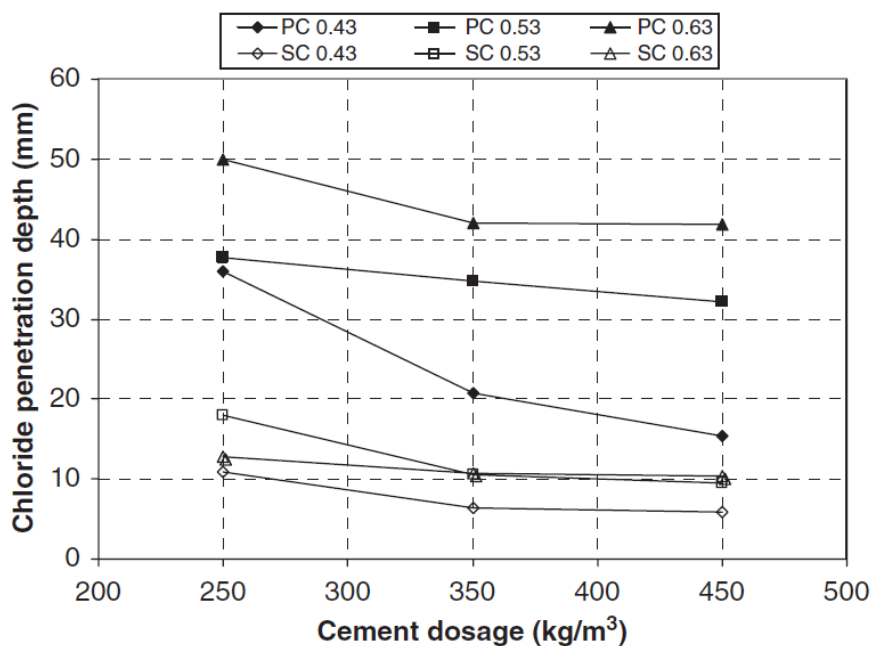


Figure 30: Chloride penetration depth for mixes with varying cement contents and w:c ratios (Yiğiter, et al., 2007)

### 2.3.3. Influence of the ITZ

Concrete can be described as a composite material composed of coarse aggregate in a hardened mortar matrix. However, one of the most integral components of the concrete matrix is the interfacial transition zone (ITZ). The ITZ is an anhydrous zone of cement grains that exists at the paste-aggregate interface and is typically 20-50 $\mu\text{m}$  thick. It is characterised as having a higher capillary porosity, generally larger pores and higher CH volume fractions than the bulk cement paste. Figure 31 below shows significantly increased porosity closer to aggregate surface. (Taylor, 1997)

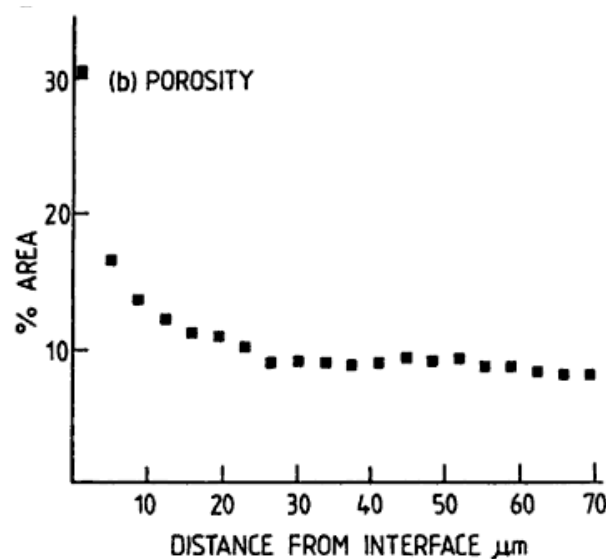


Figure 31: Porosity within ITZ in relation to the distance from the aggregate surface (Taylor, 1997)

In order to improve the durability properties of concrete, the penetrability of the ITZ needs to be decreased. Ballim et al. (2009) suggest that the ITZ may be modified through the introduction of fine fillers such as CSF or shear mixing of concrete with a low water content. Modifying concrete mixes to ensure ITZ's do not inhibit the durability potential of the concrete should be a priority for all projects.

### 2.3.4. Water: Binder Ratio

Reducing w:b ratio results in refinement and densification of the microstructure. (Dhir & McCarthy, 2011)

Figure 32 and 33 illustrate that increasing w:b ratio results in improved durability properties; a decrease in permeability and conductivity respectively.

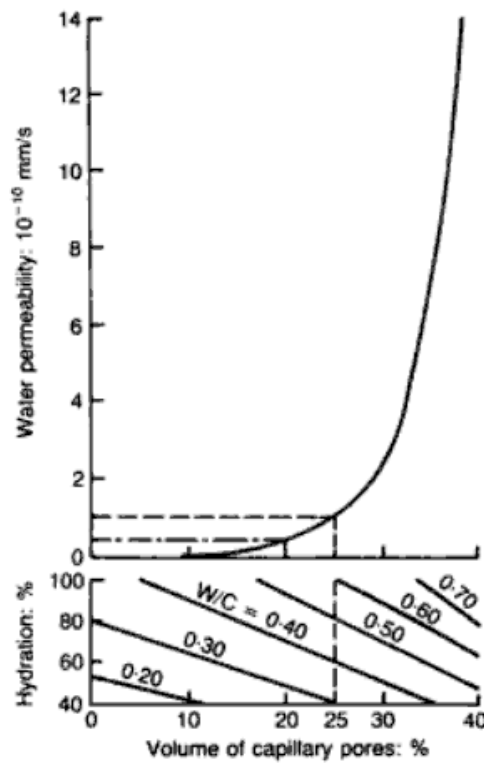


Figure 32: Influence of water: cement ratio on permeability (Comité Euro-International du Béton, 1997)

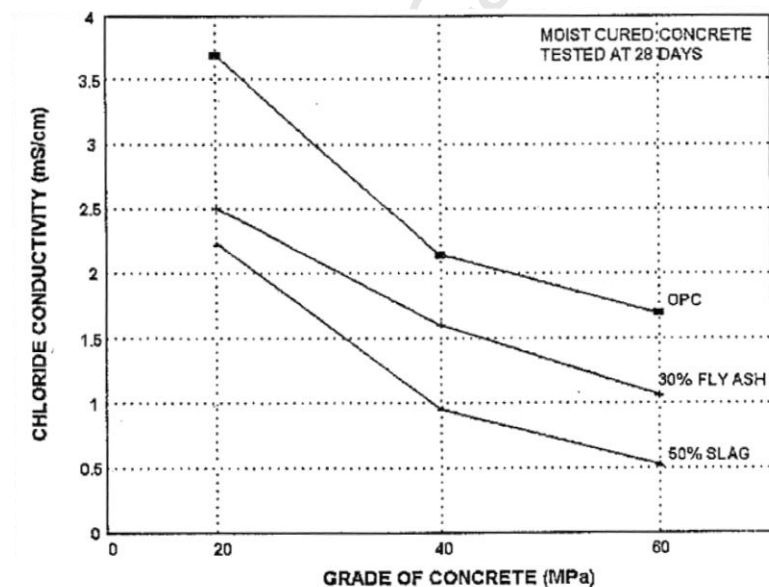


Figure 33: Chloride conductivity of concretes with varying  $w:b$  ratios and binder types (Alexander, et al., 1999)

Richardson (2002) specifies that the  $w:b$  ratio chosen, combined with the curing regime, must be sufficient to enable the capillary network to remain water filled long enough to ensure sufficient hydration.

### 2.3.5. Concrete Cover

The bulk of durability problems concern the corrosion of reinforcing steel rather than deterioration of the concrete fabric itself. The adequacy of the concrete cover layer is therefore critically important in resisting aggressive agents from the surrounding environment. (Mackechnie & Alexander, 2002)

SANS10100-2 (SABS, 1994) gives minimum cover depths, Table 6, for concretes exposed to various conditions of exposure. These are minimum depths of cover and the suggested values are based on the assumption of acceptable curing conditions during construction. (Ballim, et al., 2009)

Table 6: Minimum cover required for normal- and low-density concrete for various exposure conditions  
(SABS, 1994)

| 1  | 2                      | 3        | 4      | 5           | 6       |
|--|------------------------|----------|--------|-------------|---------|
| Concrete   | Minimum cover          |          |        |             |         |
|  | mm                     |          |        |             |         |
|  | Conditions of exposure |          |        |             |         |
|  | Mild                   | Moderate | Severe | Very severe | Extreme |
| Normal-density concrete  | 20                     | 30       | 40     | 50          | 60      |
| Low-density concrete   | 20                     | 40       | 50     | 60          | 70      |
| NOTE - This table should be used in conjunction with table A.8 of annex A. |                        |          |        |             |         |

Figure 34 illustrates the importance of cover depth in negating the effect of deleterious substances affecting the reinforcing. One can see that decreasing the cover depth to half of the nominal value can lead to a risk of decreasing the service life by up to 85 years.

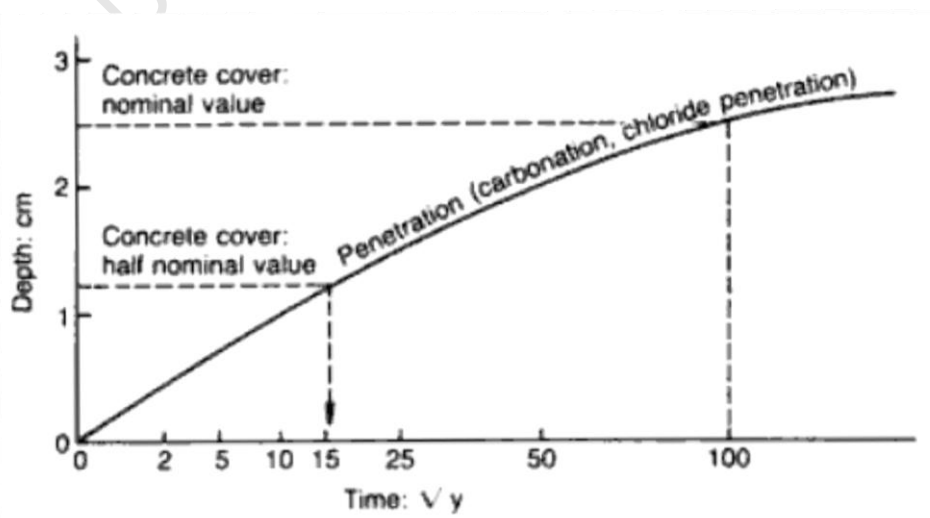


Figure 34: Effect on cover depth on time to carbonation (Comité Euro-International du Béton, 1997)

Achieving the required cover depths on construction sites is often not a simple matter and requires attention, particularly supervision. In areas where reinforcing steel bars are spliced or overlapped, the overlap should be in a plane that is parallel to the surface of the concrete. If the plane of overlap is at right angles to the surface of the concrete, the cover depth could be reduced by the diameter of the steel bar. (Ballim, et al., 2009)

### 2.3.6. Production and Construction Processes

Several novel methods of enhancing concrete performance have been developed recently. These include, self-cure concrete and controlled permeability formwork, aimed at enhancing the concrete microstructure. (Dhir & McCarthy, 2011)

Current construction techniques have been found to be more than satisfactory in producing durable concrete. The use of SCM's, improved materials and prolonged curing can undoubtedly result in vastly improved durability properties. However, more often than not, contractors will take shortcuts due to severe time and economic constraints. This can often lead to a poor quality of workmanship, whether it is mixing, batching, adequate shuttering and cover blocks or compaction and curing.

Recent developments have also seen the introduction of mix proportioning techniques, which are aimed at physically minimising the void space of concrete prior to concrete production. (Dhir & McCarthy, 2011)

There is often a lack of understanding as to the importance of each of these processes. This mindset needs to be changed through adequate supervision and the education of contractors.

#### *Compaction*

Curing is an on-site practice that needs to be well implemented and managed. Although it is outside the scope of this dissertation and somewhat of a social aspect, on-site practices need to be discussed in short. The issue of construction quality and variability must be firmly grasped before a rational approach to durability design can be achieved. During construction, variations in concrete production, curing conditions and workmanship may produce large variations in the obtained concrete quality. Thus, the in situ properties may be different from that specified or documented based on laboratory testing. For all concrete structures where durability and long-term performance are of great importance (Gjørv, 2002)

The compaction, or consolidation, of concrete is employed in order to expel entrapped air. Compaction can be achieved by hand or by mechanical means. Mechanically compacted concrete is the preferred method of consolidation and is usually achieved with internal or external vibratory equipment. Vibrated concrete undergoes a liquefaction phase due to the eradication of the internal friction between the particles within the fresh concrete matrix. (Kellerman, 2009)

Poorly compacted concrete can lead to a decrease in strength and increase in permeability. It has been shown that an entrapped air content of 5% can lead to a strength reduction of up to 30%. (Addis, B J, 1986) Figure 35 gives an indication of how the presence of air voids can lead to a significant decrease in the compressive strength of concrete. The relationship depicted below agrees with the literature discussed by Addis (1986). Leemann et al. (2006) found that improved compaction has a significant influence on the porosity and width of the ITZ of the concrete. It was found that poor compaction resulted in a lower compressive strength, higher oxygen permeability and higher water conductivity. (Leemann, et al., 2006)

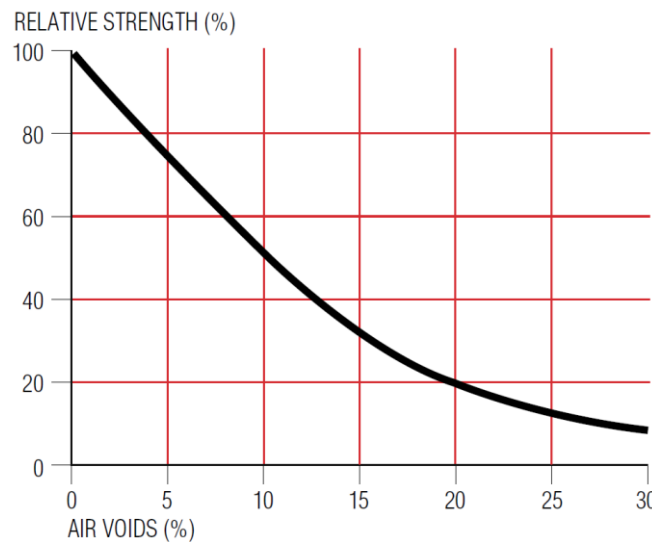


Figure 35: Relationship between air voids and relative strength of concrete (Cement Concrete & Aggregates Australia, 2006)

Kellerman (2009) states the the following consequences of poor compaction:

- Honeycombing
- Excessive entrapped air
- Sand streaks
- Cold joints
- Placement lines
- Subsidence cracking

Each of the above mentioned consequences can severely affect the penetrability of concrete. The presence of an excessive amount of honeycombing, entrapped air and cold joints will lead to an increase in penetrability of the concrete and have unfavourable consequences for the service life of the proposed structure.

Compaction is not the focus of the testing procedures employed in this dissertation, however is it a construction technique that is of critical importance to the final durability properties of the concrete

## 2.4. Concrete Durability in South Africa

Durability in South Africa is becoming of increased importance. Stringent specifications are being established by clients and authorities, thus necessitating the need for improved techniques in producing durable concrete. Durability specifications are becoming crucial in the design of structural concrete.

In the past, prescriptive approaches were taken in design. This meant that improved durability was considered to be proportional to increasing compressive strength and decreasing w:b ratio. However, recent analysis has shown that deterioration is not limited by high strength concrete. South Africa, along with many other countries, has shown that a lack of standards regarding durability in construction and design in this manner has led to the long term deterioration of many concrete structures.

More recently, there has been a move towards performance base specifications in the design of concrete structures. The durability of concrete must be seen as an interaction between the concrete system and its environment. This implies that structural performance and environmental setting criteria need to be considered. (Ballim, et al., 2009) In South Africa, a Durability Index (DI) approach has been developed in order to quantify the quality of the cover layer in terms of engineering parameters; material, processing, and environmental factors and can be immediately useful to designers and concrete specialists. These quantifiable parameters can then form the basis for crafting performance-based specifications. (Alexander, et al., 2007), (Beushausen & Alexander, 2008)

Durability is defined as the ability of a structure to retain its integrity throughout its intended service life without requiring major maintenance or a significant loss in serviceability (Addis, B J, 1986); (Ballim, et al., 2009) This infers that a concrete structure must be constructed in such a way to ensure that it fulfils its required service life.

## 2.5. Reinforcement Corrosion

The corrosion of steel reinforcement is one of the principal causes of failure in structural concrete. (Kim & Stewart, 2000) Corrosion is an electrochemical process whereby a metal undergoes a reaction with chemical species, principally oxygen and water, in the environment to form a compound. These compounds are expansive in nature and cause internal stresses within the concrete, leading to expansive cracking and loss of structural integrity, as shown in Figure 36. (Richardson, 2002)

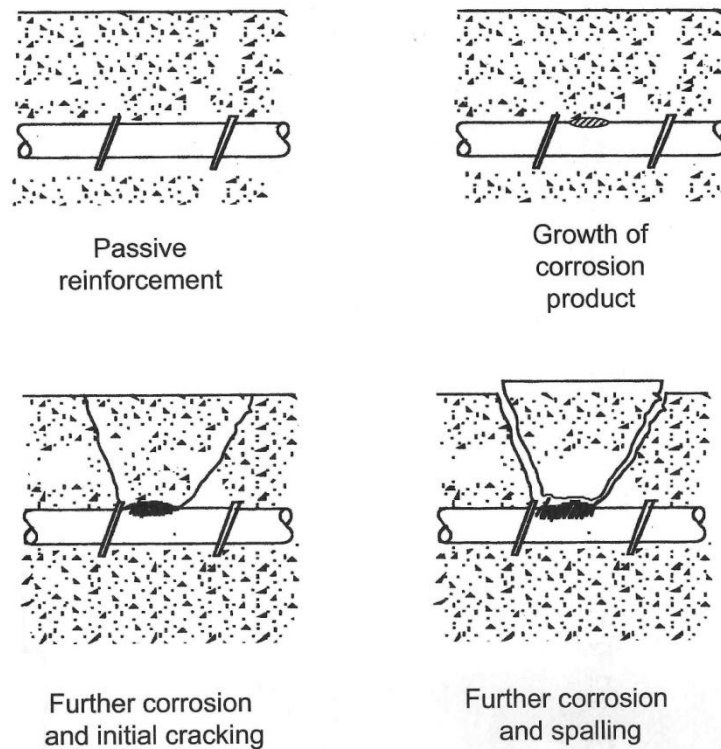


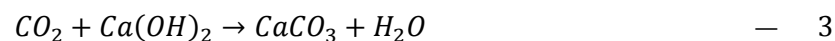
Figure 36: Stages of corrosion induced damage (Richardson, 2002)

Carbonation and chloride diffusion are the most common deleterious processes that occur in concrete in South Africa. Both processes can have dire consequences for the reinforcing steel in concrete. The influence of the aforementioned processes will be discussed below.

### 2.5.1. Carbonation

The ingress of  $\text{CO}_2$  into the pore structure of hardened concrete is a deleterious process that can have severe consequences for reinforced concrete. Carbonation involves a reaction between atmospheric  $\text{CO}_2$  and  $\text{CH}$  found in the cement paste, resulting in the formation of  $\text{CaCO}_3$ . (Kosmatka, et al., 2003)

Initiation of the reaction process requires the ingress of  $\text{CO}_2$  gas into the concrete pore structure. The  $\text{CO}_2$  then reacts with  $\text{Ca}(\text{OH})_2$  to form  $\text{CaCO}_3$ , shown in Equation 3 below:



The consumption of the  $\text{CH}$  results in a decrease in the pH of the pore water, once complete carbonation has occurred, from approximately 12.5/12.6 to 8.3/8.5. (Basheer, et al., 2001) The movement of the carbonation reaction has been described as a 'front', in that, carbonation can only continue through the concrete once all the carbonatable material has been consumed at a particular point. Once the carbonation front has reached the level of the reinforcing, Figure 37, the decrease in pH results in the depassivation of the gamma ferric oxide layer. Once this

depassivation has occurred, corrosion will commence should there be sufficient moisture and oxygen available. (Ballim, et al., 2009), (Richardson, 2002)

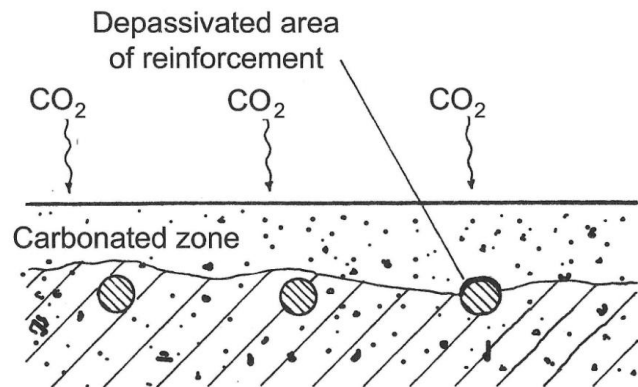


Figure 37: Ingress of carbonation to reinforcing steel. (Richardson, 2002)

The rate of carbonation can be defined as: (Richardson, 2002)

$$x = Dt^n \quad \text{— 4}$$

$x$  = depth of carbonation (mm)

$t$  = exposure time (years)

$n$  = usually 0.5 (can vary between 0.4 and 0.6)

$D$  = carbonation coefficient (mm/year<sup>0.5</sup>)

A study by Mackechnie et al. (2002) undertook to determine the effect of wet and dry curing and binder type on the carbonation depth of concrete test samples. The “Moist” cured samples were wet cured for the first 7 days whereas the “Dry” cured samples had no wet curing. The carbonation depths obtained are given in Table 7. It was found that the presence of SCM's increased the rate of carbonation of the concrete and, hence, the carbonation coefficient. This was the case for varying grades of concretes. This is due to the decrease of carbonatable material within the concrete. It can also be seen that the the initial period of wet curing improved the resistance to the ingress of CO<sub>2</sub> into the concrete. This is because prolonged wet curing benefits the hydration within the concrete cover layer, decreasing the interconnectivity and size of the pores within the concrete matrix.

Table 7: Carbonation depths for concrete exposed to different environments - 4 years exposure  
(Mackechnie & Alexander, 2002)

| Grade (MPa) | Initial Curing | PC 80% | PC 60% | FA 80% | FA 60% | SL 80% | SL 60% |
|-------------|----------------|--------|--------|--------|--------|--------|--------|
| 20          | Moist          | 13.0   | 18.5   | 13.0   | 21.5   | 15.0   | 23.5   |
|             | Dry            | 14.0   | 21.0   | 17.0   | 37.0   | 20.0   | 41.0   |
| 40          | Moist          | 5.0    | 9.5    | 5.0    | 10.0   | 6.0    | 14.5   |
|             | Dry            | 6.0    | 12.0   | 6.0    | 13.0   | 9.0    | 24.5   |
| 60          | Moist          | 1.0    | 3.0    | 1.5    | 6.0    | 2.0    | 4.5    |
|             | Dry            | 2.0    | 6.0    | 2.0    | 14.0   | 3.0    | 18.5   |

Fattuhi (1986) conducted research into the effects of mix constituents and periods of moist curing on the carbonation depth. It was found that increased periods of moist curing were significantly more beneficial in decreasing carbonation depth for samples with higher w:b ratios. There is little difference between the carbonation depths obtained for the samples with w:b = 0.4 for each of the moist curing periods. Figure 38 presents results comparing the effect of a range of periods of moist curing on the depth of carbonation obtained with prolonged periods of CO<sub>2</sub> exposure. The depth of carbonation is negligibly different for the samples moist cured for between 3 and 28 days, however, there is generally a decrease in depth with prolonged moist curing. (Fattuhi, 1986)

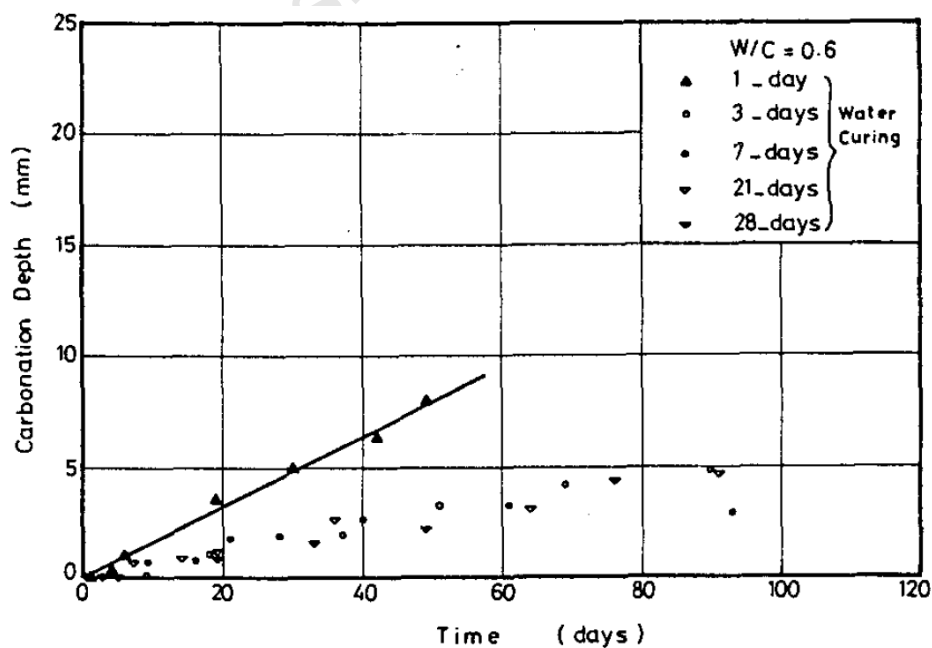


Figure 38: Carbonation depth vs. time comparing varying periods of moist curing (Fattuhi, 1986)

### 2.5.1.1. Factors Affecting Carbonation

Primary factors influencing the rate of carbonation include binder type, permeability, reserve alkalinity, environmental CO<sub>2</sub> concentration and exposure conditions. (Ballim, et al., 2009), (Richardson, 2002)

#### *Binder Type*

As discussed above in Section 2.5.1, the amount of carbonatable material strongly influences the rate of carbonation. Pozzolans are composed of the same oxides as clinker, but in different proportions and mineralogical compositions. The rate of carbonation increases as cement replacement by SCM increases. For cement replacement by an SCM the total amount of carbonatable constituents decreases due to decrease in total CH, resulting in higher carbonation rates. It has been found that concrete made with blended cements is subject to more rapid carbonation than normal Portland cement concrete. (Papadakis, 2000)

The trade off is that the SCM's refine the pore structure and ITZ within the concrete by acting as a fine filler and a site for the nucleation of hydration products. (Grieve, 2009)

#### *Permeability*

Although the ingress of CO<sub>2</sub> is governed by diffusion, permeability is generally used to indicate its resistance to carbonation. Permeability is influenced by cement content, w:b ratio, aggregate grading, degree of compaction and adequacy of curing. (Taylor, 1997) Lower permeability results in a greater resistance to the inward diffusion of CO<sub>2</sub> into the concrete. Another important factor is the curing technique and period implemented at time of construction.

#### *Alkalinity*

The resistance of concrete to carbonation also depends on the concentration of CH present. This is due to the ability of the carbonation front to progress through the concrete only once that level of concrete has been fully carbonated. Concretes comprising of pozzolans contain less CH. A decreased CH content leads to an increased rate of carbonation. However, this is by and large counteracted as the use of SCM's generally results in a refined pore structure and, therefore, decreased permeability.

#### *Environmental CO<sub>2</sub> Concentration*

The rate of carbonation increases with increasing CO<sub>2</sub> concentrations, due to the fact that diffusivity is a gradient driven transport mechanism. Higher CO<sub>2</sub> concentrations generally result in increased rates of carbonation.

### *Exposure Condition*

Carbonation occurs at an increased rate in periods of cyclic wetting and drying. Dry periods allow for the permeation of CO<sub>2</sub> whilst wet periods promote the corrosion of the reinforcing steel. It can then be inferred that carbonation cannot occur should the pores be continuously dry or water filled. A RH of approximately 65% is generally believed to be the optimum condition for carbonation, being dry enough to allow rapid gaseous diffusion of carbon dioxide whilst allowing sufficient moisture for the carbonation reaction to proceed. (Mackechnie & Alexander, 2002)

### *Temperature*

The temperature affects the reaction rate of the carbonation reaction. Furthermore, depending on the temperature, the dissolution and saturation degrees of different species with water change. At lower temperatures the reaction rate will be reduced. A relative increase or decrease in amount of carbonation products as affected by the temperature can be considered as negligible in the range of ambient temperatures, 5°C - 30°C, in South Africa. (Salvoldi, 2010)

### **2.5.2. Chloride Ingress**

Reinforcing cast into concrete forms a passive gamma ferric oxide layer due to the high alkalinity; pH approximately 12.5 - 13.5; of the CH rich pore water in the concrete matrix. This passive layer may be affected by the presence of chloride ions, which have diffused into the concrete during what is known as the initiation period. Chlorides entering concrete normally exist as weakly and strongly chemically bound. Their rate of transport is influenced by the state of chloride present. It is the free ions in the pore fluids that are considered to represent the main threat to steel reinforcement, since they are capable of further penetration into concrete and breakdown of the passive film when present in sufficient quantities at reinforcement sites. The different binder types have different capabilities in chloride binding. (Dhir, et al., 1996) The silicate phases probably make little contribution, while the aluminate phases have a major role in the binding of chloride. The use of materials rich in Al<sub>2</sub>O<sub>3</sub>, SCM's, are therefore likely to bring benefits to concrete in chloride containing environments. This benefit can also be ascribed to the refined pore structure that results from the appropriate use of SCM which, in turn, results in reduced permeability and ionic diffusivity. (Dhir & McCarthy, 2011), (Thomas, et al., 2012)

Chloride ions act as catalysts in the disruption of the passive ferric oxide layer. A minimum concentration of chlorides at the steel, known as the threshold level, is required to depassivate reinforcement under normal alkaline conditions. Values of threshold concentrations are given below in Table 8. Activation of corrosion has been found to occur at chloride levels of 0.4 - 0.5% by mass of cement, while high corrosion rates generally occur at higher chloride levels.

Once the steel is effectively depassivated, the corrosion rate and subsequent damage will depend on micro-effects such as availability of oxygen and moisture and macro-effects such as structural geometry, anode/cathode ratios and general ambient conditions. (Mackechnie, 2001)

Table 8: Qualitative risk of corrosion based on chloride levels (Mackechnie & Alexander, 2001)

| Chloride content by mass of cement (%) | Probability of corrosion |
|--|--------------------------|
| < 0.4                                  | Low                      |
| 0.4 - 1.0                              | Moderate                 |
| > 1.0                                  | High                     |

Once depassivation has fully occurred, the propagation phase commences i.e. corrosion takes place. The corrosion rate depends on micro-effects such as availability of oxygen and moisture and macro-effects such as structural geometry, anode and cathode ratios and general ambient conditions. (Mackechnie, 2001)

Figure 39, below, diagrammatically represents the diffusion of chlorides into the concrete cover layer and the subsequent propagation of corrosion.

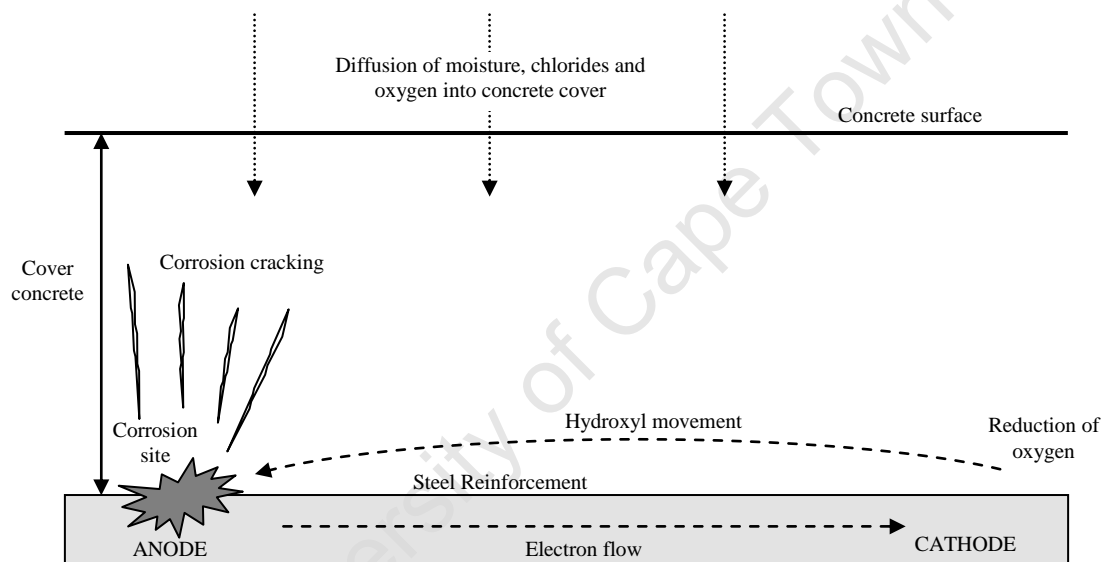


Figure 39: Corrosion of steel reinforcement in concrete (Mackechnie, 2001)

## 2.6. Transport Mechanisms Affecting Durability

### 2.6.1. Permeation

Permeation is the movement of fluids through the pore structure of the concrete by an externally applied pressure, with the pores being saturated with the fluid under consideration. In the case of water retaining structures, this may be due to a hydrostatic pressure head. The permeability of concrete is dependent on concrete pore structure, degree of interconnection of pore structure and moisture content of the material. (Ballim, et al., 2009), (Alexander, et al., 1999), (Richardson, 2002), (Basheer, et al., 2001)

Characteristics of the permeating fluid are important in determining the coefficient of permeability as the characteristics of the permeating fluid are unique in each situation. Gases

having varying compressibility and viscosity and is considered when calculating the coefficient of permeability.

Equation 5 can be used to calculate the coefficient of permeability: (Kropp & Hilsdorf, 1995)

$$K_g = \eta \frac{Ql}{tA} \frac{2p}{(p_1 - p_2)(p_1 + p_2)} \quad \text{--- 5}$$

$K_g$  = coefficient of permeability ( $\text{m}^2$ )

$\eta$  = viscosity of the gas ( $\text{Ns}/\text{m}^2$ )

$Q$  = volume of gas ( $\text{m}^3$ )

$l$  = thickness of section (m)

$A$  = surface area of section ( $\text{m}^2$ )

$p$  = pressure the volume of gas is measured ( $\text{N}/\text{m}^2$ )

$p_1$  = pressure gas enters sample ( $\text{N}/\text{m}^2$ )

$p_2$  = pressure gas exits sample ( $\text{N}/\text{m}^2$ )

$t$  = time (s)

Permeability is used in the prediction of carbonation depths in concrete. (Ballim, et al., 2009)

### 2.6.2. Absorption

Absorption is the process whereby fluid is drawn into a porous, unsaturated material under the action of capillary forces. The transport of liquid by capillary rise is caused by the pressure differential across the meniscus. The capillary suction is dependent on the pore geometry and the degree of saturation of concrete. Water absorption caused by wetting and drying at the concrete surface is an important transport mechanism near the surface but becomes less significant with depth. The rate of movement of a wetting front through a porous material under the action of capillary forces is defined as sorptivity. Sorptivity may be defined using Equation 6: (Richardson, 2002)

$$\frac{V}{A} = S t^{0.5} \quad \text{--- 6}$$

$V$  = volume of material absorbed in time  $t$  ( $\text{mm}^3$ )

$A$  = cross sectional surface area of section ( $\text{m}^2$ )

$S$  = Sorptivity ( $\text{mm}/\text{min}^{0.5}$ )

$t$  = time (min)

Sorptivity is influenced by the larger capillaries and their degree of interconnection, and is very sensitive to hydration of the outer concrete surface, therefore curing is extremely important in the way it influences the sorptivity properties within the cover layer. It is also influenced by

compaction and aggregate orientation and distribution, and by mix composition. (Ballim, et al., 2009)

### 2.6.3. Diffusion

Diffusion is the movement of ions in the pore solution due to the difference in concentration gradient of the two regions. Diffusion requires that the pores be partially or fully saturated and is an important transport mechanism for the movement of chlorides into the concrete. Fick's second law of diffusion is used to model ionic diffusion and Crank's error function solution, shown below in Equation 7, of Fick's second law is commonly used to quantify chloride concentrations at depth. (Ballim, et al., 2009), (Kropp & Hilsdorf, 1995), (Costa & Appleton, 1999), (Kosmatka, et al., 2003)

Concentration profiles observed in laboratory or on-site specimens are evaluated using Equation 7 by means of a regression analysis. (Kropp & Alexander, 2007)

$$C_{(x,t)} = C_s \left[ 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{D_a t}} \right) \right] \quad - \quad 7$$

$C_{(x,t)}$  = chloride concentration at depth  $x$  at a given time  $t$

$C_s$  = surface chloride concentration ( $\text{g}/\text{m}^3$ )

$D_a$  = apparent chloride diffusion coefficient ( $\text{m}^2/\text{s}$ )

$t$  = time of exposure (s)

$\operatorname{erf}$  = mathematical error function

The ingress of ions through the concrete matrix is generally treated as a diffusion process. However, surface concentrations of chlorides are formed due to absorption in the convection zone. Cyclical wetting and drying at the surface inhibits the development of a pure diffusion mechanism. However, below the convection zone further movement of chlorides occurs due to diffusion. Figure 40, below, depicts this phenomena. The ingress of chlorides into concrete thus occurs partly due to a combination of the various transport mechanisms. (Ballim, et al., 2009), (Kropp & Alexander, 2007)

Diffusion coefficients are used in the development and calibration of service life models and important in the determination of service life durability predictions.

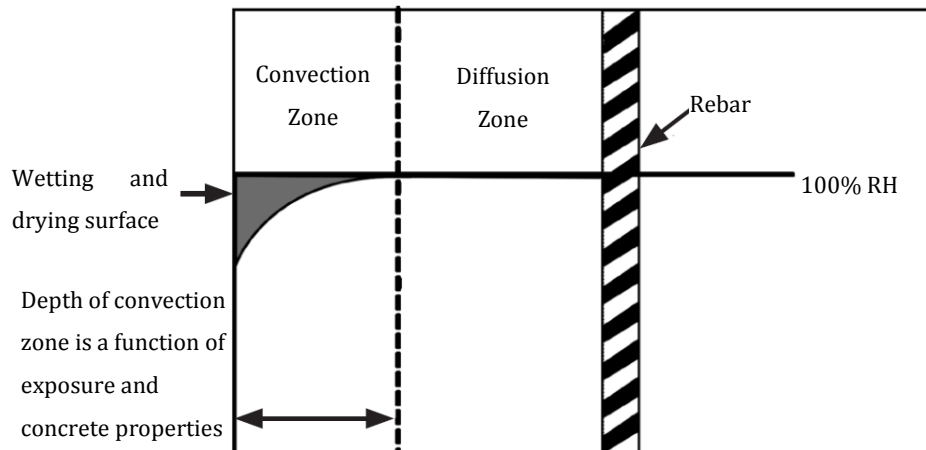


Figure 40: Zones depicting zones of transport mechanisms at differing depth (Ballim, et al., 2009)

#### 2.6.4. Combined Transport Processes

The action of any of the above mentioned transport mechanisms rarely occur in isolation and may represent an over-simplification of the real transport processes. Each of the transport mechanisms may function in combination at any given time or individually in different sections in the concrete matrix along the flow path. (Ballim, et al., 2009).

#### 2.6.5. Transport Properties of Cracked Concrete

Cracking in concrete can have a severe effect on the service life of a concrete structure by increasing the rate at which deleterious substances ingress into the concrete. (Otieno, et al., 2010) The durability properties may be compromised by various factors, such as member geometry and loading, variability in concrete properties, volumetric changes in the concrete, amount and distribution of the reinforcement, and bond between the concrete and reinforcement. (Boulfiza, et al., 2003)

Microcracks will always exist at a microscopic level due to stresses forming at the paste-aggregate interface and due to variations in curing conditions, especially at surface level. Microcracks may also form as a result of drying shrinkage and corrosive interactions with the environment (Kropp & Alexander, 2007)

The main parameters for describing flow in damaged and sound material are different. Figure 41, below, illustrates the considerable effect cracking can have on the rate of chloride ingress. In uncracked concrete permeability is related to its porosity, while in cracked concrete it is related to crack properties.

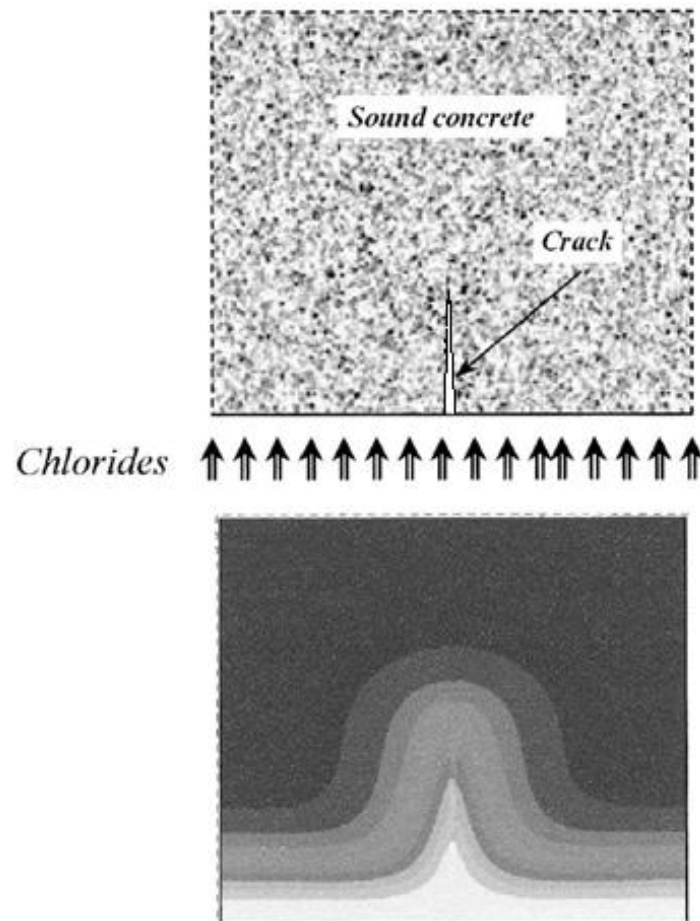


Figure 41: Rational model for chloride ion transport prediction for cracked concrete element (Boulfiza, et al., 2003)

Regardless of the transport mechanism, properties of the cracks can become more important in cracked concrete than the properties of the concrete itself. Parameters such as crack width and shape, crack density/frequency and degree of connectivity, as well as crack origin, govern transport in cracked concrete. (Ballim, et al., 2009) The prediction of crack influence on transport mechanisms is not the topic of the following study, however, the effect on curing on the development of microcracks is. It is therefore important to understand that curing will indirectly influence the transport of deleterious substances through cracked concrete.

## 2.7. Specifications

South African specifications do not identify curing procedures to be implemented in adverse weather conditions. It is the evaporation of pore water from the cover layer of the concrete that is most important in influencing the durability properties of the concrete. Thus, specifications need to be put in place ensuring that adequate curing practices are implemented. SANS 10100-2:1994 gives the following recommended curing techniques:

### 2.7.1. Normal Conditions

- ponding or continuous sprinkling of the exposed surfaces with water;
- covering the concrete with sand, or with mats made of a moisture-retaining material, and keeping the covering continuously wet;
- the continuous application of steam (not exceeding 60°C) or mist spray;
- covering the concrete with waterproof or plastics sheeting firmly anchored at the edges;
- the use of an approved curing compound, applied in accordance with the manufacturer's recommendations.

The curing procedures described previously are rarely performed and inadequately maintained. The most commonly used curing technique is the wetting of concrete surfaces, allowing water to pond. The use of hessian or plastic to reduce evaporation is rarely implemented and spray on curing compounds are expensive and hard to apply sufficiently. (Chan, et al., 1999)

BS 8110-1:1997 provides a specified minimum curing duration, Table 9, based on binder types for two ranges of concrete surface temperatures.

*Table 9: Minimum Periods of Curing and Protection* (BSI Subcommittee B/525/2, 1997)

| Type of Cement  | Ambient Conditions After Casting                                | Minimum Periods of Curing and Protection |              |
|---|---|--|--------------|
|   |   | Average Surface Temperature of Concrete  |              |
|   |   | 5°C to 10°C                              | 10°C to 25°C |
|   |   | Days                                     | Days         |
| PC 42.5 or PC 52.5 to BS 12<br>SRPC 42.5 to BS 4027   | Average   | 4  | 1 - 3        |
|   | Poor  | 6  | 2 - 4        |
| All cements indicated in Table 1 of BS 5328-1:1997 except for PC42.5 or PC 52.5 to BS 12, SRPC 42.5 to BS 4027 and supersulfated cement | Average   | 6  | 2 - 4        |
|   | Poor  | 10                                       | 4 - 7        |
| All   | Good  | No special requirements                  |              |
| NOTE 1:<br>Abbreviations for the type of cement used are as follows:  |   |  |              |
| PC 42.5:  | Portland cement (class 42.5) (see BS 12);                       |  |              |
| PC 52.5:  | Portland cement (class 52.5) (see BS 12);                       |  |              |
| SRPC 42.5:  | Sulfate-resisting Portland cement (class 42.5) (see BS 4027).   |  |              |
| NOTE 2:<br>Ambient conditions after casting are as follows:   |   |  |              |
| Good:   | damp and protected (RH > 80%; protected from sun and wind);     |  |              |
| Average:  | intermediate between good and poor;                             |  |              |
| Poor:   | dry or unprotected (RH < 50%; not protected from sun and wind). |  |              |

### 2.7.2. Hot Weather Conditions

The following procedures may be adopted to reduce the placing temperature of the concrete: (SABS, 1994)

- shielding aggregate stockpiles (and all metal surfaces in contact with aggregates) from the direct rays of the sun;
- cooling aggregate stockpiles by spraying with water;
- using chilled water or ice flakes for mixing water; and
- injecting liquid nitrogen into the concrete during mixing.

ACI Committee 305 (1999) state that curing needs to be implemented as soon as placing and finishing has been completed. Methods include:

- moist curing
- membrane curing
- curing of concrete in forms

The code specifies that the gist of curing concrete in hot weather is to protect the concrete from high temperature, direct sunlight, low humidity, and drying winds.

### 2.7.3. Cold Weather Conditions

When the concrete is placed at ambient temperatures below 5°C, the temperature of the concrete shall not be below 10°C, for which purpose heating of the water or of the aggregate shall be permitted. Heated water and aggregate shall first be mixed and the cement added only while the temperature of the mixture is below 30°C. The temperature of placed concrete shall not be allowed to fall below 5°C until the concrete has attained a strength of at least 5 MPa. (SABS, 1994)

ACI Committee 306 (2002) detail two parts to curing of concrete in cold weather; curing during and following the protection period. Following the removal of the temperature protection, it is usually not necessary to provide measures to prevent excessive drying.

Drying will be, for example, excessive if concrete at 20°C is exposed to air having a temperature of 10°C and a RH less than 40 %.

### 2.7.4. South African National Roads Agency Ltd (SANRAL)

SANRAL has implemented durability limits for their major construction projects throughout South Africa. These limits are prescribed in order to ensure the service life of the structure is achieved. Values are based on research performed by the Universities of Cape Town and the Witwatersrand, giving required DI values for a 100 year service life based on service life models.

Table 10 and Table 11, below, provide the prescribed limits for all structural concrete in environments where carbonation or chloride induced corrosion may occur.

Table 10: Concrete Durability Specification Targets - Carbonation Induced Corrosion

| Designation | Cover Depth (mm) | In-situ DI Value for various Cover Depths - 100 Year Life |                   |
|-------------|------------------|---|-------------------|
|             |                  | OPI (log scale)   | Sorptivity (mm/h) |
|             |                  | Recommended value   | Recommended value |
| XC1a        | 40               | n/a   | 10.0              |
| XC1b        | 40               | 9.20  | 10.0              |
|             | 50               | 9.00  | 10.0              |
|             | 60               | n/a   | n/a               |
| XC2         | 40               | 9.40  | 10.0              |
|             | 50               | 9.10  | 10.0              |
|             | 60*              | 9.00  | 10.0              |
|             | 70*              | n/a   | n/a               |
| XC3         | 40               | 9.40  | 10.0              |
|             | 50               | 9.10  | 10.0              |
|             | 60*              | 9.00  | 10.0              |
|             | 70*              | n/a   | n/a               |
| XC4         | 40               | 9.60  | 10.0              |
|             | 50               | 9.30  | 10.0              |
|             | 60*              | 9.10  | 10.0              |
|             | 70*              | 9.00  | 10.0              |

WARNING: Covers shown with a asterisk (\*) should be avoided so as to (i) limit crack widths, and (ii) ensure durability concrete is being specified and must be discussed with the client before being specified

NOTE: Heavily Polluted Industrial Areas: Increase cover for any exposure condition above by 10 mm

Table 11: Concrete Durability Specification Targets - Chloride Induced Corrosion

| Designation | Cover Depth (mm) | In-situ Durability Index for various Cover Depths - 100 Year Life |                     |                     |                    | Sorptivity (mm/h) |
|-------------|------------------|---|---------------------|---------------------|--------------------|-------------------|
|             |                  | Recommended CCI (mS/cm)   |                     |                     |                    |                   |
|             |                  | Typical Binder Blends   |                     |                     |                    |                   |
|             |                  | 70:30<br>CEM I:FA   | 50:50<br>CEM I:GGBS | 50:50<br>CEM I:GGCS | 90:10<br>CEM I:CSF |                   |
| XS1         | 40               | 1.50  | 1.60                | 2.10                | 0.40               | 10.0              |
|             | 50               | 2.10  | 2.20                | 2.80                | 0.50               | 10.0              |
|             | 60               | 2.60  | 2.70                | 3.40                | 0.65               | 10.0              |
| XS2a        | 40               | 1.00  | 1.10                | 1.40                | 0.30               | 10.0              |
|             | 50               | 1.40  | 1.60                | 2.00                | 0.40               | 10.0              |
|             | 60               | 1.80  | 2.10                | 2.50                | 0.50               | 10.0              |
| XS2b        | 60               | 1.45  | 1.70                | 2.00                | 0.40               | 10.0              |
| XS3a        | 40               | 0.65  | 0.85                | 1.00                | 0.25               | 10.0              |
|             | 50               | 1.10  | 1.35                | 1.45                | 0.35               | 10.0              |
|             | 60               | 1.45  | 1.70                | 2.00                | 0.40               | 10.0              |
| XS3b        | 60               | 1.10  | 1.30                | 1.55                | 0.30               | 10.0              |

The highest OPI value required is 9.60 in exposure class XC4 for 40mm of cover. Chloride conductivity values are very sensitive to binder type and therefore cannot be generally classified as with OPI values. All limits described above are easily achievable with adequate mix designs. The problem lies in the fact that due to a required decrease in the use of concrete materials, from both an economic and environmental perspective, the durability of concrete may be neglected whilst trying to curtail economic expenditure. However, savings in material use may be compensated for with properly implemented curing procedures.

### 2.7.5. Environmental Considerations

Environmental conditions in South Africa vary considerably due to the wide range of climatic zones that exist.

Table 12, below, illustrates the general conditions experienced throughout South Africa. The values given are the averages experienced in these cities over a 30 year period. Full data sets are given in Appendix A.

*Table 12: Climatic Data for major South African Cities for period 1961 – 1990*

*[Adapted from data retrieved from WeatherSA]*

| Mean             |                       | Cape Town |        | Johannesburg |        | Durban |        | Kimberley |        |
|------------------|-----------------------|-----------|--------|--------------|--------|--------|--------|-----------|--------|
|                  |                       | Summer    | Winter | Summer       | Winter | Summer | Winter | Summer    | Winter |
| Temperature (°C) | Highest Recorded      | 41        | 39     | 35           | 36     | 37     | 31     | 40        | 36     |
|                  | Daily Maximum         | 25        | 19     | 25           | 27     | 24     | 19     | 31        | 22     |
|                  | Daily Minimum         | 14        | 9      | 19           | 20     | 14     | 7      | 16        | 6      |
|                  | Lowest Recorded       | 1         | -1     | 0            | 8      | 3      | -8     | 7         | -8     |
| Precipitation    | Monthly (mm)          | 19        | 67     | 100          | 113    | 56     | 19     | 53        | 16     |
|                  | No. of days with >1mm | 36        | 68     | 79           | 87     | 44     | 21     | 52        | 21     |

The inland highveld areas (Johannesburg) have hot, wet summers and cold, dry winters with a generally lower humidity.

The subtropical east coast (Durban) has hot, wet summers and warm, dry winters, with an especially high humidity all year round.

The Mediterranean-type south-west (Cape Town) and southern coastlines experience mild, wet winters and dry, hot summers.

The arid western interior (Kimberley) experiences hot summers when the maximum rainfall occurs and cold, dry winters, where night time temperatures fall well below freezing.

South Africa experiences both extremely cold and hot conditions. Thus, normal, hot and cold weather concreting conditions need to be considered in all concrete construction applications.

Generally construction activities occur during the day, thus negating the effect of the cold weather on the initial curing period. Average temperatures generally fall above the temperature given as the upper limit, 4-5°C, of "cold weather" conditions. However, more often than not, temperatures throughout South Africa exceed the lower limit, 32°C, of "hot weather" conditions.

### 2.7.6. Hot Weather Concreting

Hot weather conditions need to be defined so that manufacturers are aware of the ambient conditions that may adversely affect the final durability properties of the concrete in question. Curbing moisture loss from the surface layer is of the utmost importance and the supply of excess moisture will further aid the hydration of the concrete, improving the impermeability. High temperatures and loss of moisture may cause thermal and plastic shrinkage and a reduction in strength and durability. (SABS, 1994) Hot weather is defined as a combination of any of the following conditions that may lead to excessive evaporation: (ACI Committee 305, 1999), (Nabil, et al., 2010)

- high ambient temperature, defined by Kellerman (2009) as being greater than 32°C
- high concrete temperature
- low relative humidity
- high wind velocity
- solar radiation.

Kellerman (2009) also states that conditions may be defined as "hot weather" conditions should the temperature exceed 25°C and any of the following ambient conditions be present:

- low relative humidity
- high wind velocity
- solar radiation
- high concrete temperatures

The above specifications both identify similar environmental considerations, however, differ slightly in the temperature defined. This does not notably influence the overall curing requirements, as temperatures in this high range, 25 - 32°C, will inevitably negatively affect the durability properties of the concrete if not taken into consideration.

Potential deficiencies to concrete in the hardened state may include: (ACI Committee 305, 1999), (Alsayed & Amjad, 1994), (Cement, Concrete & Aggregates Australia, 2004)

- decreased 28 day strengths resulting from either higher water demand or higher concrete temperature, or a combination of both at time of placement and during the first few days;
- increased tendency for drying shrinkage and differential thermal cracking ;
- increased risk of cracking, resulting in decreased durability;
- greater variability of surface appearance, such as cold joints or colour difference, due to different rates of hydration or different w:b ratios;
- increased potential for the ingress of corrosive solutions; and
- increased permeability as a result of high water content or inadequate curing.

With respect to durability, hot weather concreting negatively affects the durability properties of the concrete due to an increased rate of evaporation and mix concrete temperature lead to excessive plastic shrinkage and cracking which can lead to an increase in the rate of carbonation and chloride ingress due to increased penetrability. It is therefore in these extreme conditions that protection of the concrete after placement is crucial.

Figure 42 and Figure 43 below, both depict the negative effect of higher ambient temperatures on fresh and hardened concrete properties. Figure 42 illustrates the effect of increasing ambient temperature on the water demand of concrete for a given slump of 75mm. Often, on site, more water will be added to the concrete to improve its workability if it has been left standing or if initial setting time has been reduced due to higher ambient temperatures. Figure 43 depicts the effect of prolonged ambient temperatures on the compressive strength of the hardened concrete.

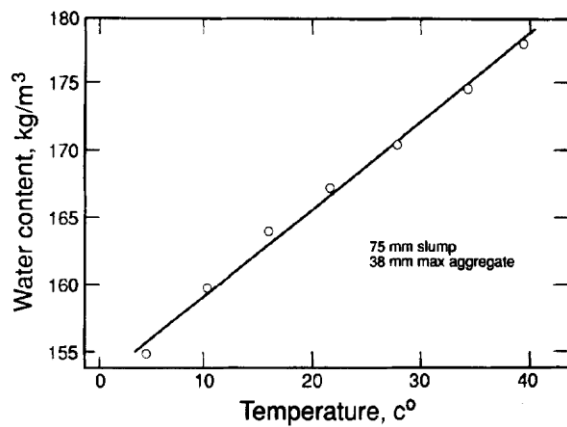


Figure 42: Effect of ambient temperature on water demand of concrete mix (Soroka & Ravina, 1998)

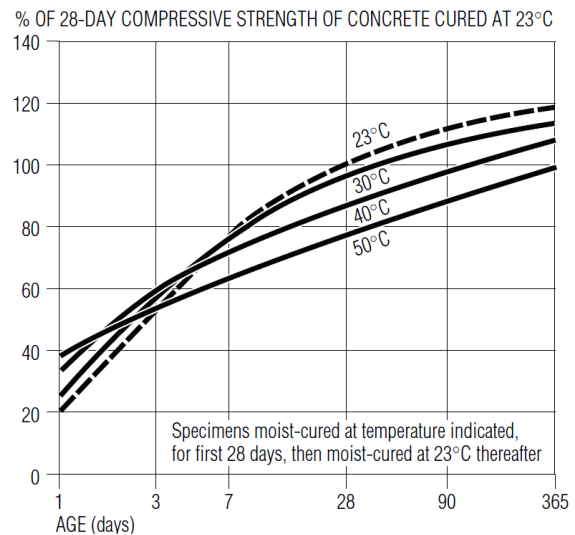


Figure 43: Effect of ambient temperatures on compressive strength (Cement, Concrete & Aggregates Australia, 2004)

There are practical ways, with respect to curing procedures, to reduce effects of high temperatures on concrete properties: (Kellerman, 2009)

- confine, where possible, concreting to the cooler parts of the day;
- a suitable retarder may be used in the mix; this will aid in maintaining the workability of the concrete without requiring additional water, leading to an increase in w:b ratio;
- if feasible, the area to be concreted should be sheltered from high winds and direct sunlight;
- formwork may be cooled by occasionally spraying it with water;
- placing and compacting must be carried out carefully and systematically to minimise the formation of cold joints, which act as pathways for the movement of deleterious substances; and
- curing and protection must be done in such a way as to minimise heat gain.

The use of extenders, FA and GGBS, also aids in reducing the heat of hydration, thus aiding in reducing the overall high temperatures affecting the concrete.

Precautions have to be taken into account when concrete is being placed in hot, windy and low humidity environments. Placing concrete in extremely hot environments can have a significant effect on the final concrete properties.

### 2.7.7. Cold Weather Concreting

Cold weather conditions, as with the hot weather described above, need to be defined so that manufacturers are aware of the ambient conditions that may adversely affect the final durability properties of the concrete in question. Managing heat loss from the concrete is the main priority during the initial curing period. (Kellerman, 2009) Extremely cold weather conditions are not of great significance in South Africa, but can be an issue in some circumstances. Cold weather is defined as such when the average daily temperature drops below 4°C for a period of more than 3 consecutive days. Should the ambient temperature exceed 10°C for more than 12 hours in 1 day, the environmental conditions are no longer classified as “cold weather”. (ACI Committee 308, 1998), (SABS, 1994)

Cold weather puts immature concrete at risk in the following ways: (ACI Committee 308, 2001)

- the rate of evaporation of water from the surface of concrete can be higher in cold weather than in warm weather, particularly when the concrete is warm and the humidity is low;
- if the concrete temperature greatly decreases, pore water can freeze in the pores of the concrete, leading to expansion and cracking;
- cold concrete temperature slows the rate of hydration of the cement, slowing the rate at which the concrete properties develop; and
- when protection is removed at the end of the curing period, there is a risk of rapid drying, and a rapid drop in temperature can crack the concrete.

Figure 44 and 45 illustrate the effect of colder ambient temperatures on the initial setting time and 28 day compressive strength respectively.

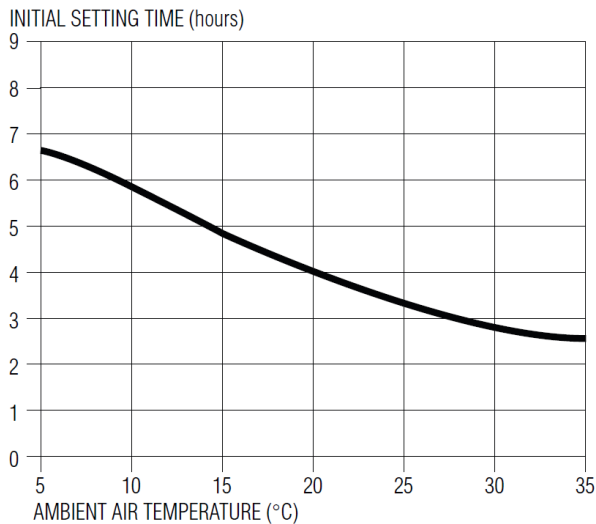


Figure 44: Effect of lower ambient temperatures on the initial setting time of concrete (Cement, Concrete & Aggregates Australia, 2004)

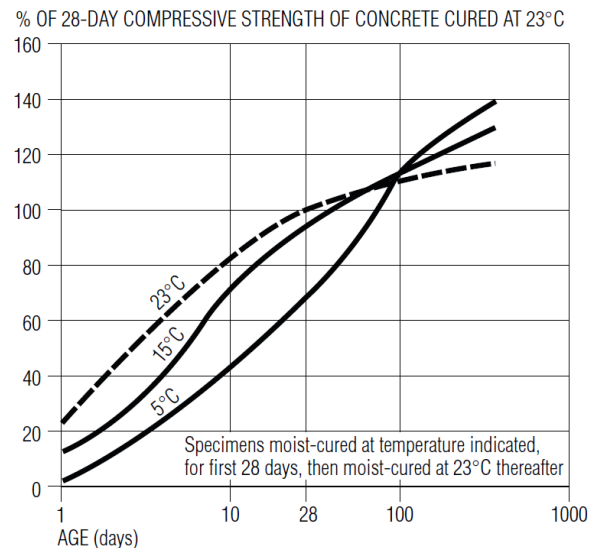


Figure 45: Effect of lower ambient temperatures on the compressive strength of concrete (Cement, Concrete & Aggregates Australia, 2004)

Data presented by Nmai (1998), Table 13, illustrates the effect of decreasing ambient temperatures on the setting time of concrete.

Table 13: Influence of ambient temperature on the final setting time of CEM I concrete (Nmai, 1998)

| Temperature (°C) | Approximate Time of Setting(hours) |
|------------------|------------------------------------|
| 21               | 6                                  |
| 16               | 8                                  |
| 10               | 10                                 |
| 4                | 14                                 |
| -1               | 19                                 |
| -7               | No set - concrete freezes          |

As stated before, the main priority of curing in cold weather is to prevent heat loss from the freshly placed concrete. Kellerman (2009) states that under no circumstances should water curing methods be used. However, moist curing in freezing weather can be beneficial to the long-term durability of the concrete, but only if the moist concrete is kept from freezing. Curing in cold weather can require a temporary enclosure with internal heating, membrane-forming curing compounds or plastic coverings. These techniques may or may not produce the equivalent concrete surface properties as providing added water, but the risk of freezing damage to the concrete surface is reduced. (Kellerman, 2009), (ACI Committee 308, 2001)

## 2.8. Conclusion

The preceding chapter sought to discuss, in detail, literature regarding the transport mechanisms affecting performance, deterioration processes of concrete and the effect of various curing techniques on concrete durability. Each of these factors is well documented and has been substantially researched for many years.

Established curing techniques; water, hessian, plastic covering, curing compounds, as well as the lack of curing; have been used for decades. However, differences in materials properties result in vastly different inherent properties in the final concrete product. This was evident in the literature studied. Modern technologies, crystallising PRA's and improved curing compounds, necessitate continued review of the effects of use.

Prolonged moist curing of concrete has been shown to significantly benefit the durability properties of concrete. Hessian and clingwrap may be of benefit, however, the implementation of the methods may define whether or not they are effective. Literature has shown that they do improve the durability properties. Crystallising PRA's have been shown to be negligibly beneficial in comparison to immersion of concrete and marginally beneficial compared to other wet and sealing cured methods. An integral waterproofer may prove more effective than spray on curing compounds as they may be more efficiently mixed into the concrete as opposed to unevenly applied to concrete surfaces. Integral waterproofers claim to have a self healing ability whereas curing compounds will fail should cracks appear in the concrete.

The effect of the curing environment determines the curing method required. Hot and dry environments usually require moist and/or sealing methods to inhibit the evaporation of pore water from the cover layer. Cool and wet environments are typically less harsh to the hydrating concrete and implementation of certain methods may, in actual fact, prove to be damaging in their use. Colder conditions may require heating sources to ensure the hydration reaction is not adversely affected.

The effects of curing depend largely on correctly implemented construction techniques. Implementing adequate curing regimes properly on site may lead to significantly reduced penetrability of the concrete.

## CHAPTER THREE

### 3. Experimental Methodology

#### 3.1. Introduction

The experimental work was performed in order to ascertain the effects of various curing and mix design parameters on the durability properties of concrete. The parameters included varied curing techniques, binder types and w:b ratios. The aim of the experiments is to reinforce the importance of curing to the final durability properties and determine the influence that newer technologies may offer.

The mix designs specified are those commonly used in the construction industry. Binder replacement proportions and w:b ratios are common and literature is readily available as to the benefits of the quantities utilised.

The curing techniques employed are commonly used. The techniques implemented varied between well established techniques to newer technologies. Water cured samples were used as a 'best case' reference. Samples were also exposed to winter and simulated summer environments in the Western Cape, South Africa. Hessian, an emulsified paraffin wax and a solvent based curing compound, clingwrap and two crystallising PRA's were used as the various curing methods in one or more of the curing environments.

The experiments performed are standard tests used to determine the various durability properties based on the transport mechanisms within the concrete cover layer. The 28 day compressive strength, South African Durability Index, bulk diffusion and accelerated carbonation tests were performed. The compressive strength test was not used as an indicator of inherent durability, more so to support that curing affects compressive strength as well as durability.

The results will be used to determine how the curing techniques and binder type selection may be used to achieve specified durability limits.

#### 3.2. Experimental details

##### 3.2.1. Mix Designs and Specimen Manufacture

The mix designs used in the study were based on those used by Salvoldi (2010) and follow the standard mix designs used by industry.

The w:b ratios used are representative of those used within industry and give a range indicative of the effects of w: b ratio on durability properties. Lower w:b ratios were chosen as reviewed

literature states that improvement in durability properties is proportional to decreasing w:b ratios. The bulk of the specimens produced and tested have a w:b ratio of 0.4 due to the associated improvement of the durability properties.

The SCM proportions chosen are the standard industry replacement percentages and common values for cement replacement in South Africa. The proportions chosen have also been shown to be beneficial to the durability properties obtained by concrete samples tested in past studies. Alexander et al. (1999), Aldea et al. (2000) and Thomas et al. (2004) illustrate the effectiveness of the binder types and the proportions selected for use.

Table 14 lists the mix designs and the materials used. Four binder types were utilised for the reasons discussed above. The three w:b ratios specified were only used for the 100% CEM I 42.5N cement concrete samples. The range of w:b ratios were not used for the SCM blended samples due to the limited time of study.

Table 14: Mix Designs

| Material (kg/m <sup>3</sup> )   |                  | 100 % CEM I 42.5N |       |       | 50% CEM I/<br>50% GGBS | 70% CEM I/<br>30% FA | 90% CEM I/<br>10% CSF |
|---------------------------------|------------------|-------------------|-------|-------|------------------------|----------------------|-----------------------|
| Water/binder ratio              |                  | 0.4               | 0.5   | 0.6   | 0.4                    | 0.4                  | 0.4                   |
| Binder                          | PC (CEM I 42.5N) | 425.0             | 340.0 | 283.3 | 212.5                  | 323.8                | 382.5                 |
|                                 | GGBS             | -                 | -     | -     | 212.5                  | -                    | -                     |
|                                 | FA               | -                 | -     | -     | -                      | 138.8                | -                     |
|                                 | CSF              | -                 | -     | -     | -                      | -                    | 42.5                  |
| Fine Aggregate                  | Klipheuwel sand  | 740               | 825   | 882   | 740                    | 740                  | 740                   |
| Coarse Aggregate                | Greywacke (19mm) | 1050              |       |       |                        |                      |                       |
| Water content ( <i>litres</i> ) |                  | 170               |       |       |                        |                      |                       |
| Admixture (kg)                  | PRA2 (1%)        | 4.3               | 3.4   | 2.8   | 4.3                    | 4.6                  | 4.3                   |
|                                 | PRA1 (1.5%)      | 6.4               | 5.1   | 4.2   | 6.4                    | 6.9                  | 6.4                   |
| Superplasticiser required (%)   |                  | 0.56              | -     | -     | 0.54                   | 0.40                 | 0.62                  |

Table 15 and Table 16 indicate the volume of concrete that was required for each of the curing techniques tested. 12 and 7 l of concrete were required for the w:b = 0.4 and w:b = 0.5 & 0.6 samples respectively. In each case, 15 l of concrete was batched and mixed in order to ensure that there was excess concrete available and the samples had a consistent composition.

Table 15: Samples required for concrete mixes ( $w:b = 0.4$ )

| Test                 | Sample Number | Sample Type | Litres |
|----------------------|---------------|-------------|--------|
| Compressive Strength | 3             | 3 Cubes     | 3      |
| OPI                  | 4             | 2 Cubes     | 2      |
| WSI                  |               |             |        |
| CCI                  | 4             | 2 Cubes     | 2      |
| Carbonation          | 4             | 2 Cubes     | 2      |
| Bulk Diffusion       | 3             | 3 Cubes     | 3      |
|                      |               |             | 12     |

Table 16: Samples required for concrete mixes ( $w:b = 0.5$  and  $0.6$ )

| Test                 | Sample Number | Sample Type | Litres |
|----------------------|---------------|-------------|--------|
| Compressive Strength | 3             | 3 Cubes     | 3      |
| OPI                  | 4             | 2 Cubes     | 2      |
| WSI                  |               |             |        |
| Carbonation          | 4             | 2 Cubes     | 2      |
|                      |               |             | 7      |

0.015m<sup>3</sup> of concrete was batched and mixed for each of the mix designs specified above in accordance with SANS 5861-1:2006. All mixes required a slump of between 75 and 125 mm to ensure adequate workability. A slump test was performed in accordance with SANS 5862-1:2006. Superplasticiser was added to all of the mixes with a  $w:b$  ratio of 0.4 in order to obtain the required slump. The CEM I sample ( $w:b = 0.5$ ) required no superplasticiser to obtain the required slump, with the CEM I sample ( $w:b = 0.6$ ) obtaining a slump of 150mm. Fifteen 100x100x100 mm cubes were cast for each mix in accordance with SANS 5861-3:2006. Demoulding was carried out 24 hours after casting and specified curing technique applied.

### 3.3. Curing Methods

The various curing techniques discussed below represent a wide range of the curing methods employed by industry today. Each is discussed in past literature to various degrees. The effect of curing compounds and crystallising PRA's is something that cannot be definitively stated due to the varying nature of the proprietary chemicals produced and developments in newer technologies. The curing compounds and crystallising PRA's utilised in this study are those that are available in South Africa.

#### 3.3.1. Water Cured

Water curing was used in order to obtain results to be used as references and as a "best case" environment. Water curing is used for compressive strength and durability index testing for laboratory manufactured specimens, and therefore provides better results than what would be achieved on site. All water cured samples were placed in a curing bath for 28 days at  $23 \pm 2^\circ\text{C}$  in accordance with SANS 5861-3:2006.

### 3.3.2. Winter Curing (Exposed Outside - Western Cape, South Africa)

The samples tested with this curing method were placed in an uncontrolled outdoor environment immediately after demoulding, Figure 46.



Figure 46: Storage area for samples exposed to environmental conditions

The samples were left exposed to winter conditions for the entire 28 day period. This was in order to establish the effect of lower temperatures and excess moisture due to high precipitation levels. Temperature, RH and rainfall levels were monitored throughout the period and recorded. See Figure 47 for the RH and precipitation conditions and Appendix B - Curing Conditions for the temperature conditions. It must be noted that no rain fell for 3 weeks from the beginning of July.

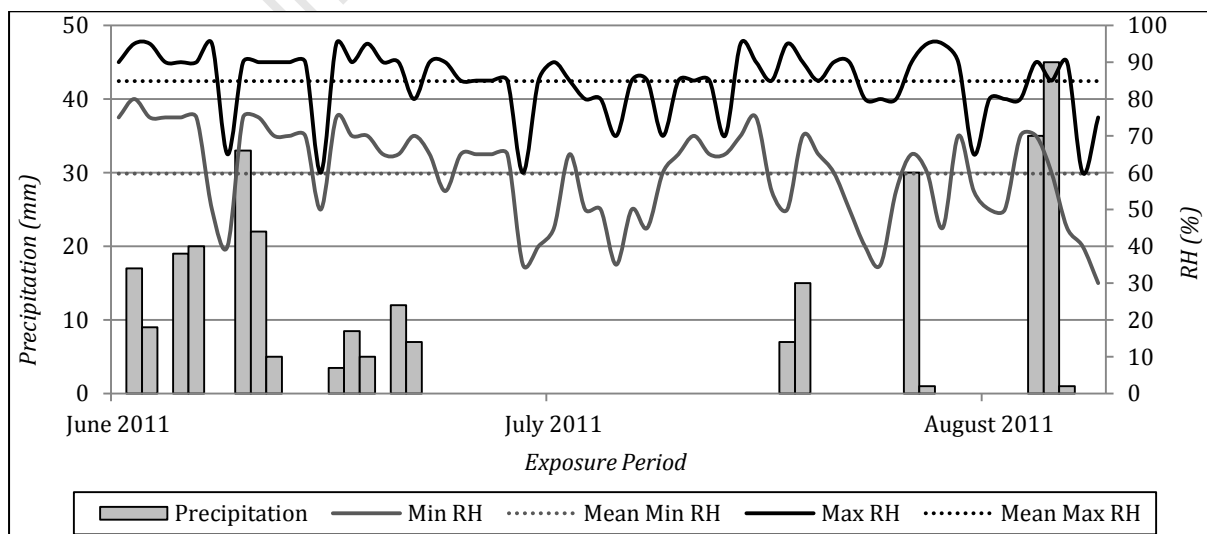


Figure 47: Winter curing conditions - max and min RH and precipitation (14 June - 16 August 2011)

### 3.3.3. “Summer” Curing (Controlled Laboratory Environment)

The uncured samples were placed in controlled laboratory conditions for a period of 28 days. Temperature and RH were kept constant at  $22\pm 2$  °C and  $45\pm 5\%$  RH. The conditions simulated “summer” conditions, whereby RH was kept low and there was no precipitation. The environment would theoretically provide a worst case scenario for young concrete to cure.

### 3.3.4. Hessian Covered

The samples were placed in the controlled laboratory conditions, discussed in Section 3.3.3 above, immediately after demoulding and wrapped in damp hessian. The hessian was wet daily and removed after 7 days. The samples were then placed in the controlled laboratory environment until the 28 day testing time, imitating samples left exposed to “summer” conditions on site.

### 3.3.5. Clingwrap

The samples were placed in the controlled laboratory conditions, discussed in Section 3.3.3 above, immediately after demoulding and wrapped in clingwrap, Figure 48. The clingwrap was removed after 7 days, imitating industry practices. The samples were then placed in the controlled laboratory environment until the 28 day testing time, imitating samples left exposed to “summer” conditions on site.



*Figure 48: Clingwrap sealed samples in controlled environment*

### 3.3.6. Curing Compounds

The curing compounds were applied to the respective samples after demoulding. Two coats of the curing compounds were brush applied to the surface of the concrete samples in accordance with manufacturer's recommendations. The samples were then placed in two different environments. One set of samples was placed in the controlled laboratory environment until the 28 day testing time, imitating samples left exposed to "summer" conditions on site. The other set of samples was placed in the exposed outside, winter, environment until the 28 day testing time.

CC1 is a solvent based white pigmented curing compound and CC2 is a liquid-emulsified paraffin wax curing compound. Both comply with ASTM C309 Type 1 or 2 Class A curing compounds. Class A curing compounds have unrestricted compositions and Type 1 and 2 curing compounds are clear or pigmented respectively.

### 3.3.7. Crystallising Waterproofers

The crystallising PRA's were added at time of mixing. They were initially mixed with some of the water included in the mix design to form a slurry. The slurry was then added to the rest of the concrete materials. Dosages were according to manufacturers' recommendations, 1.5 and 1 % by weight of binder for the PRA1 and PRA2 respectively.

The crystallising PRA's used consist of Portland cement, very fine treated silica sand and various active, proprietary chemicals. These active chemicals react with the moisture in fresh concrete and the by-products of cement hydration to cause a catalytic reaction, which generates a non-soluble crystalline formation throughout the pores and capillary tracts of the concrete. (ICS Penetron International, n.d.), (Xypex Chemical Corporation, 2009)

Table 17 gives the labelling used for the samples for each of the tests performed. The three curing environments are listed on the left and the binder types and w:b ratios on top. The various curing techniques implemented are listed for each curing environment. The labels therefore state the w:b ratio, binder type, curing environment and curing technique implemented.

Table 17: Summary of labelling used to mark samples noting w:b ratio, binder type and curing technique implemented

| Curing Technique         |               |      | Labels            |                         |                           |                          |                   |                   |
|--------------------------|---------------|------|-------------------|-------------------------|---------------------------|--------------------------|-------------------|-------------------|
|                          |               |      | w:b = 0.4 (4)     |                         |                           |                          | w:b = 0.5 (5)     | w:b = 0.6 (6)     |
|                          |               |      | 100% CEM I<br>(C) | 70% CEM I/30% FA<br>(F) | 50% CEM I/50% GGBS<br>(G) | 90% CEM I/10% CSF<br>(S) | 100% CEM I<br>(C) | 100% CEM I<br>(C) |
| Water<br>(W)             | Untreated     | (W)  | 4CW               | 4FW                     | 4GW                       | 4SW                      | 5CW               | 6CW               |
|                          | PRA1 (X)      | (WX) | 4CWX              | 4FWX                    | 4GWX                      | 4SWX                     | 5CWX              | -                 |
|                          | PRA2 (P)      | (WP) | 4CWP              | 4FWP                    | 4GWP                      | 4SWP                     | 5CWP              | -                 |
| Winter (Outside)<br>(O)  | Untreated     | (O)  | 4CO               | 4FO                     | 4GO                       | 4SO                      | 5CO               | 6CO               |
|                          | CC1 (1)       | (1O) | 4C1O              | 4F1O                    | 4G1O                      | 4S1O                     | 5C1O              | 6C1O              |
|                          | CC2 (2)       | (2O) | 4C2O              | 4F2O                    | 4G2O                      | 4S2O                     | 5C2O              | 6C2O              |
| "Summer" (Inside)<br>(I) | Hessian (H)   | (H)  | 4CH               | 4FH                     | 4GH                       | 4SH                      | 5CH               | 6CH               |
|                          | Clingwrap (C) | (C)  | 4CC               | 4FC                     | 4GC                       | 4SC                      | 5CC               | 6CC               |
|                          | Untreated     | (I)  | 4CI               | 4FI                     | 4GI                       | 4SI                      | 5CI               | 6CI               |
|                          | CC1 (1)       | (1I) | 4C1I              | 4F1I                    | 4G1I                      | 4S1I                     | 5C1I              | 6C1I              |
|                          | CC2 (2)       | (2I) | 4C2I              | 4F2I                    | 4G2I                      | 4S2I                     | 5C2I              | 6C2I              |
|                          | PRA1 (X)      | (IX) | 4CIX              | 4FIX                    | 4GIX                      | 4SIX                     | 5CIX              | -                 |
|                          | PRA2 (P)      | (IP) | 4CIP              | 4FIP                    | 4GIP                      | 4SIP                     | 5CIP              | -                 |

### 3.4. Testing Procedures

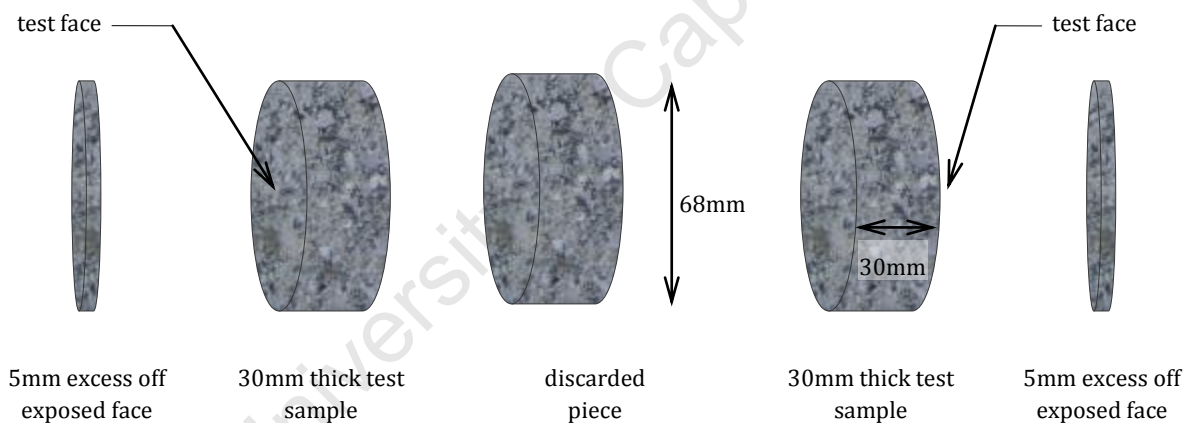
#### 3.4.1. Compressive Strength Test

All samples, Table 17, were tested for compressive strength in accordance with SANS 5863:2006. Each sample set of three 100 x 100 x 100 mm cubes was cured for 28 days with the curing procedure under investigation. All samples were placed in a water bath for a period of 24 hours prior to testing. Tests were performed using an AMSLER compression testing machine at a loading rate of  $0.3 \pm 0.1$  MPa/sec.

#### 3.4.2. Durability Index Tests

The DI tests serve as indicator of the characteristic transport properties of the cover layer of concrete.

Each test procedure required four samples. These were obtained from two cores, 68mm in diameter, cored from 2 cubes. 5mm was trimmed off of each exposed face. Two discs, 30mm thick, were then cut from each side of the core.



All DI tests were conducted in accordance with Durability Index Testing Manual Version 1 (2009) (Alexander, et al., 1999)

#### *Oxygen Permeability Index (OPI) Test*

The OPI Test procedure was performed in order to assess the air permeability of the concrete samples. Four OPI specimens were tested for each of the 74 samples sets tested in total. All of the samples listed in Table 17 underwent the OPI test. The OPI test was commenced after 28 days of each specified curing technique. The samples are placed in the test apparatus, Figure 49 and Figure 50, and subjected to oxygen pressurised in the pressure vessel to 100kPa. The pressure decay is then monitored and measured in order to determine the coefficient of permeability.



Figure 49: OPI test equipment

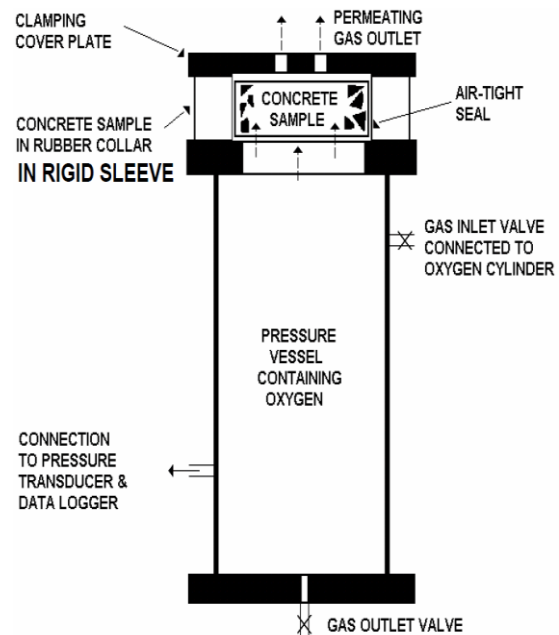


Figure 50: Detailed diagram of OPI cell arrangement

(University of Cape Town & University of Witwatersrand, 2009)

#### Water Sorptivity Index (WSI) Test

The WSI Test procedure is performed by measuring the mass of water absorbed with time from the bottom of the concrete sample, of which the sides have been sealed with packaging tape, Figure 51. All of the samples listed in Table 17 underwent the WSI test. Four WSI specimens were tested for each of the sample sets. The WSI test was commenced after 28 days.

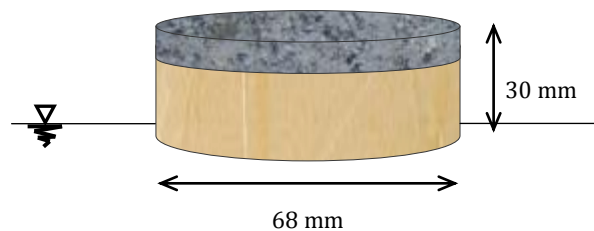


Figure 51: Sealed sample used to determine WSI

#### Chloride Conductivity Index (CCI) Test

The CCI Test procedure was performed in order to assess the chloride conductivity properties of the concrete samples. The samples with the 0.5 and 0.6 w:b ratios were not tested for

chloride conductivity. Four CCI specimens were tested for each of the sample sets. The CCI test was commenced after 28 days.

### 3.4.3. Accelerated Carbonation

The accelerated carbonation tests were only performed on selected samples due to the time constraints of the study. The samples chosen were those exposed to “summer” curing. Each of the binder types ( $w:b = 0.4$ ) were chosen for testing. However, only PRA1 and PRA2 were used as durability enhancers and an untreated sample tested to serve as a reference. Carbonation in CEM I, FA, GGBS and CSF concrete is well documented and understood. However, the inclusion of crystallising PRA’s will alter the microstructure of the concrete. Their inclusion therefore needs to be tested in order to ascertain how carbonation is affected. Samples were only exposed to the “Summer” environment due to the severely adverse affect it has on the durability properties of the concrete samples, Table 18, and therefore serves as a ‘worst case’.

Table 18: Samples used for carbonation test

| Binder             | “Summer” (Inside) | “Summer” - PRA1 | “Summer” - PRA2 |
|--------------------|-------------------|-----------------|-----------------|
| 100% CEM I         | 4CI               | 4CIX            | 4CIP            |
| 70% CEM I/30% FA   | 4FI               | 4FIX            | 4FIP            |
| 50% CEM I/50% GGBS | 4GI               | 4GIX            | 4GIP            |
| 90% CEM I/10% CSF  | 4SI               | 4SIX            | 4SIP            |

Four samples were tested for each mix design. Each of the four samples were sealed with an epoxy on all but one side, to be used as the exposed test face, as shown in Figure 52.

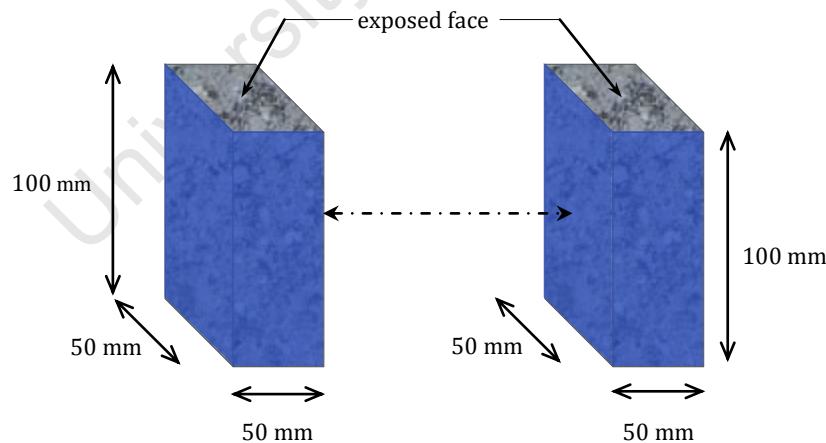


Figure 52: Preparation of samples for  $CO_2$  exposure

When concrete is saturated  $CO_2$  is unable to diffuse into the concrete. Therefore,  $CO_2$  can only diffuse as the concrete dries. It is therefore the drying rate of the concrete that governs the rate at which  $CO_2$  diffuses through the concrete, under accelerated test conditions. The samples were thus preconditioned to ensure that the drying rate of the sample would not dictate the carbonation rate during testing. (Salvoldi, 2010)

The concrete specimens were initially stored in a controlled environmental room for 60 days at a RH of  $45 \pm 2.5\%$  and temperature of  $20 \pm 2^\circ\text{C}$ . Thereafter they were placed in the carbonation chamber for 14 days where the RH was kept constant at  $65 \pm 5\%$  and the temperature was kept constant at  $20 \pm 2^\circ\text{C}$ . Subsequently the  $\text{CO}_2$  was applied and the accelerated carbonation was started at the same conditions.

The apparatus used for the accelerated carbonation was the LEEC GA2010 150l Research Incubator, Figure 53.



Figure 53: LEEC Research  $\text{CO}_2$  Incubator

The LEEC incubator controls the  $\text{CO}_2$  concentration from  $0 - 20 \pm 0.1\%$  and was set to 2%. The incubator runs at  $5^\circ\text{C}$  above ambient temperature and needed to be cooled via an external water pump placed in a bucket in a fridge-freezer. The temperature was thereby controlled at  $20 \pm 2^\circ\text{C}$ . The RH within the chamber was controlled manually by managing small amounts of water and silica crystals in the bottom of the chamber. The RH was kept at  $65 \pm 5\%$  RH.

Carbonation depth was measured at 3, 6 and 9 weeks. The specimens were removed from the chamber and the top third of the specimens was cut off perpendicular to the exposed face, Figure 54.

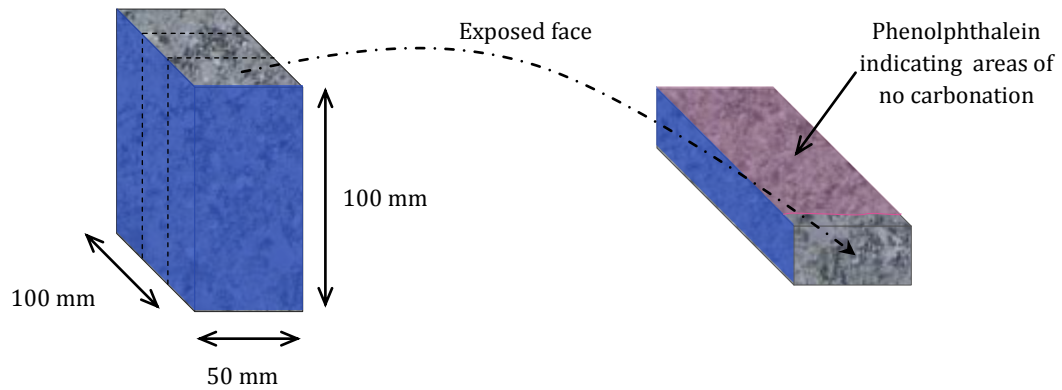


Figure 54: Method of cutting samples in order to determine carbonation depth

Phenolphthalein was then applied to the freshly cut surface and the depth of the carbonation front measured with vernier callipers. An example of the development of a carbonation front is shown in Figure 55. The cut surface of the remainder of the sample was then resealed with epoxy and the samples placed back in the carbonation chamber once the epoxy had dried.

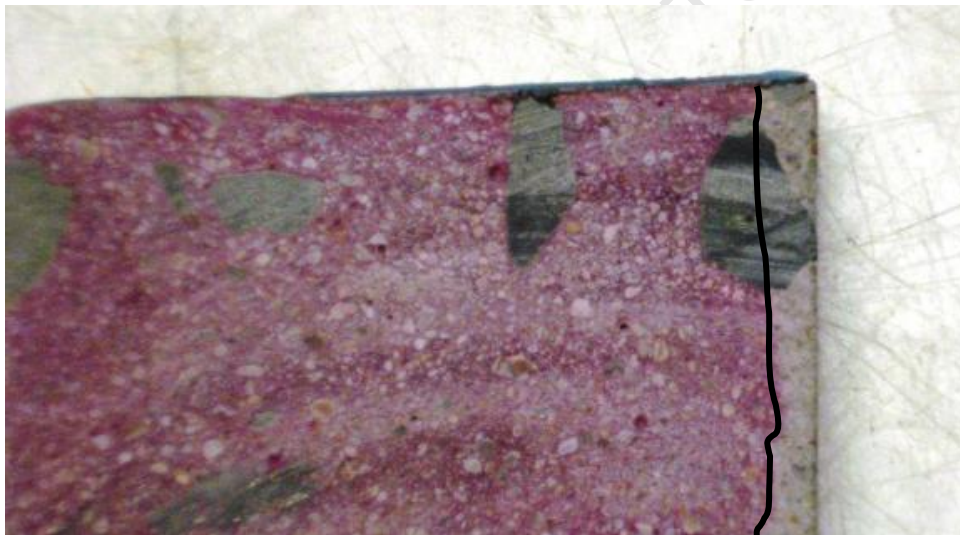


Figure 55: Carbonation (grey area) in concrete after accelerated carbonation testing

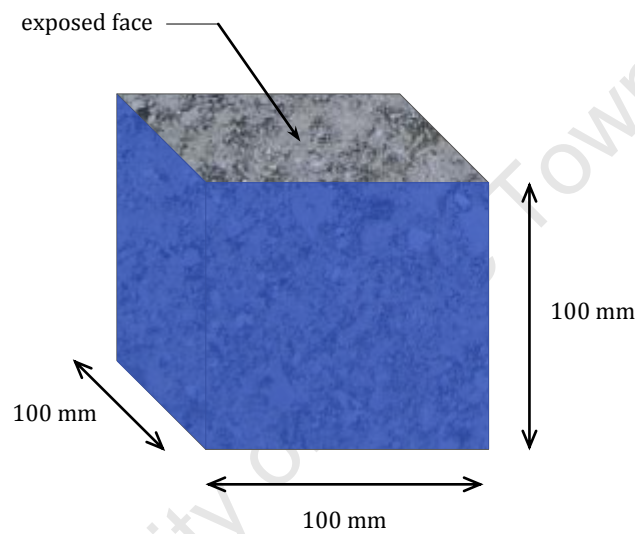
#### 3.4.4. Bulk Diffusion

The bulk diffusion test was performed on a limited set of samples for the same reasons as the carbonation testing. Concrete exposed to high chloride environments generally have higher durability properties specified. Higher durability properties are generally associated with concretes having lower w:b ratios and containing SCM's. For these reasons, samples with a w:b ratio of 0.4 were tested as it was deduced that the high durability associated with lower w:b ratio concretes would be specified in environments with high chloride concentrations. Samples were tested only in the "Summer" curing environment as this environment is considered to be a worst case for curing of concrete. Samples were treated with PRA1 and PRA2 and an untreated sample was used as a reference, Table 19.

Table 19: Samples used for bulk diffusion test

| Binder             | “Summer” (Inside) | “Summer” (Inside) - PRA1 | “Summer” (Inside) - PRA2 |
|--------------------|-------------------|--------------------------|--------------------------|
| 100% CEM I         | 4CI               | 4CIX                     | 4CIP                     |
| 70% CEM I/30% FA   | 4FI               | 4FIX                     | 4FIP                     |
| 50% CEM I/50% GGBS | 4GI               | 4GIX                     | 4GIP                     |
| 90% CEM I/10% CSF  | 4SI               | 4SIX                     | 4SIP                     |

The bulk diffusion tests were performed on three 100x100x100 mm cube samples for each mix design. Each of the four samples were sealed with an epoxy on all but one side, to be used as the exposed test face, as shown in Figure 56.

Figure 56: Preparation of samples for CO<sub>2</sub> exposure

Testing was conducted in accordance with ASTM C 1556-04. The specimens were saturated in CaOH<sub>2</sub> for 24 hours after the initial 28 days of “Summer” curing. The samples were then immersed in 2.8M NaCl solution for a period of 42 days. The samples were then ground at 4 mm depth increments, Table 20, in order to obtain six powder samples for titration testing. The chloride concentrations obtained from the titration testing were then analysed using a curve fit analysis spreadsheet in order to obtain the diffusion coefficient.

Table 20: Incremental depths for chloride analysis

| Depth | Depth Increments (mm) | Average Depth (mm) |
|-------|-----------------------|--------------------|
| 1     | 0-4                   | 2                  |
| 2     | 5-8                   | 6                  |
| 3     | 9-12                  | 10                 |
| 4     | 13-16                 | 14                 |
| 5     | 17-20                 | 18                 |
| 6     | 21-24                 | 22                 |

In certain cases, only specific samples were tested for each of the tests performed. Table 21 summarises which tests were performed on which samples.

Table 21: Summary of tests performed

|    | Test            | Water |      | Winter (Outside Curing) |     |         | Summer (Inside Controlled Curing) |     |     |      |      |   |   |   |
|----|-----------------|-------|------|-------------------------|-----|---------|-----------------------------------|-----|-----|------|------|---|---|---|
|    |                 | PRA1  | PRA2 | CC1                     | CC2 | Hessian | Clingwrap                         | CC1 | CC2 | PRA1 | PRA2 |   |   |   |
| 4C | $f_c$           | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | OPI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | WSI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CCI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CO <sub>2</sub> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
|    | Cl <sup>-</sup> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
| 4F | $f_c$           | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | OPI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | WSI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CCI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CO <sub>2</sub> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
|    | Cl <sup>-</sup> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
| 4G | $f_c$           | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | OPI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | WSI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CCI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CO <sub>2</sub> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
|    | Cl <sup>-</sup> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
| 4S | $f_c$           | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | OPI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | WSI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CCI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CO <sub>2</sub> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
|    | Cl <sup>-</sup> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
| 5C | $f_c$           | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | OPI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | WSI             | ✓     | ✓    | ✓                       | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ | ✓ | ✓ |
|    | CO <sub>2</sub> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |
| 6C | $f_c$           | ✓     |      |                         | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ |   |   |
|    | OPI             | ✓     |      |                         | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ |   |   |
|    | WSI             | ✓     |      |                         | ✓   | ✓       | ✓                                 | ✓   | ✓   | ✓    | ✓    | ✓ |   |   |
|    | CO <sub>2</sub> |       |      |                         |     |         | ✓                                 |     |     |      |      |   |   |   |

### 3.5. Summary

The above chapter set out the experimental details of the testing conducted. This included mix designs, materials used, mixing and casting procedures, curing techniques employed and tests performed. Tests were carried out in order to obtain the compressive strength, durability indexes and carbonation and chloride diffusion coefficients for each sample.

All aspects of the testing were conducted in accordance with relevant testing procedures and standards in order to ensure consistent testing procedures were adhered to.

University of Cape Town

## CHAPTER FOUR

### 4. Results and Discussion

#### 4.1. Introduction

Results obtained from the laboratory experiments will be presented and discussed in the following chapter. The primary aim of the investigation was to determine the durability properties of the concrete samples and draw a parallel with the curing procedure implemented. The DI values were evaluated according to the Durability Index Testing Manual (2009).

All results have been represented as bar graphs in order to easily draw comparisons between the curing techniques for each binder type. The water cured samples are represented in black, exposed Winter samples in dark grey and the inside “Summer” samples in light grey. The untreated reference samples are symbolised in a hatch pattern. Each curing technique will then be discussed relative to the relative reference sample i.e. water cured compared with water cured, winter with winter and summer with summer.

#### 4.2. Compressive Strength

The compressive strength of all concrete mixes was tested. Compressive strength is often considered the sole criterion for the approval of a concrete mix in the construction industry. The compressive strength is not used as a definitive indicator of inherent durability, only more so recently, as a prescriptive based approach is no longer taken. There are, however, correlations that have been found to exist between compressive strength and durability parameters. It has been found that adequate correlations are binder dependant due the influence on paste microstructure. It is understood that the same influences that control the transport processes also weigh on compressive strength development. (Al-Amoudi, et al., 2009) Conversely, however, it is becoming increasingly accepted that strength is not an adequate indicator for durability as it does not account adequately for the influence of constituent materials or construction process variables such as placing, compaction and curing. These factors affect the quality of the surface zone of the concrete and therefore have a direct influence on durability. (Ballim, et al., 2009)

The results for the 28 day compressive strength tests conducted are given below in Figure 57 and Figure 58. Table 22 provides comparative results whereby each sample is presented as a proportion of its relative reference sample, indicated in bold. Each reference sample has been presented as a value of 1 and each treated sample as a proportion of it. Therefore, a value of higher than 1 depicts that the treated samples improved the compressive strength obtained. The converse applies for values less than 1.

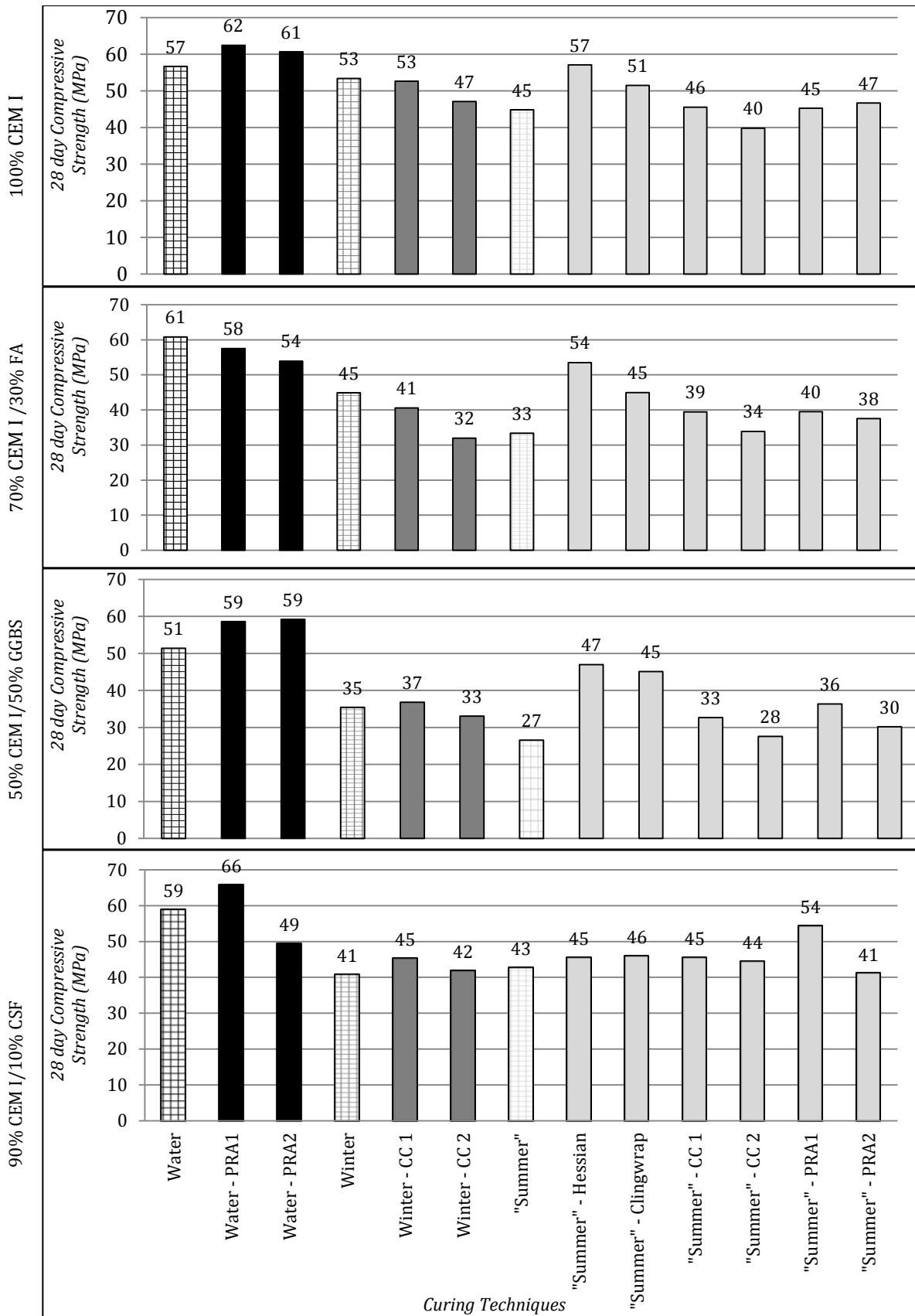


Figure 57:  $f_c$  values obtained comparing influence of curing technique and binder type ( $w:b = 0.4$ )

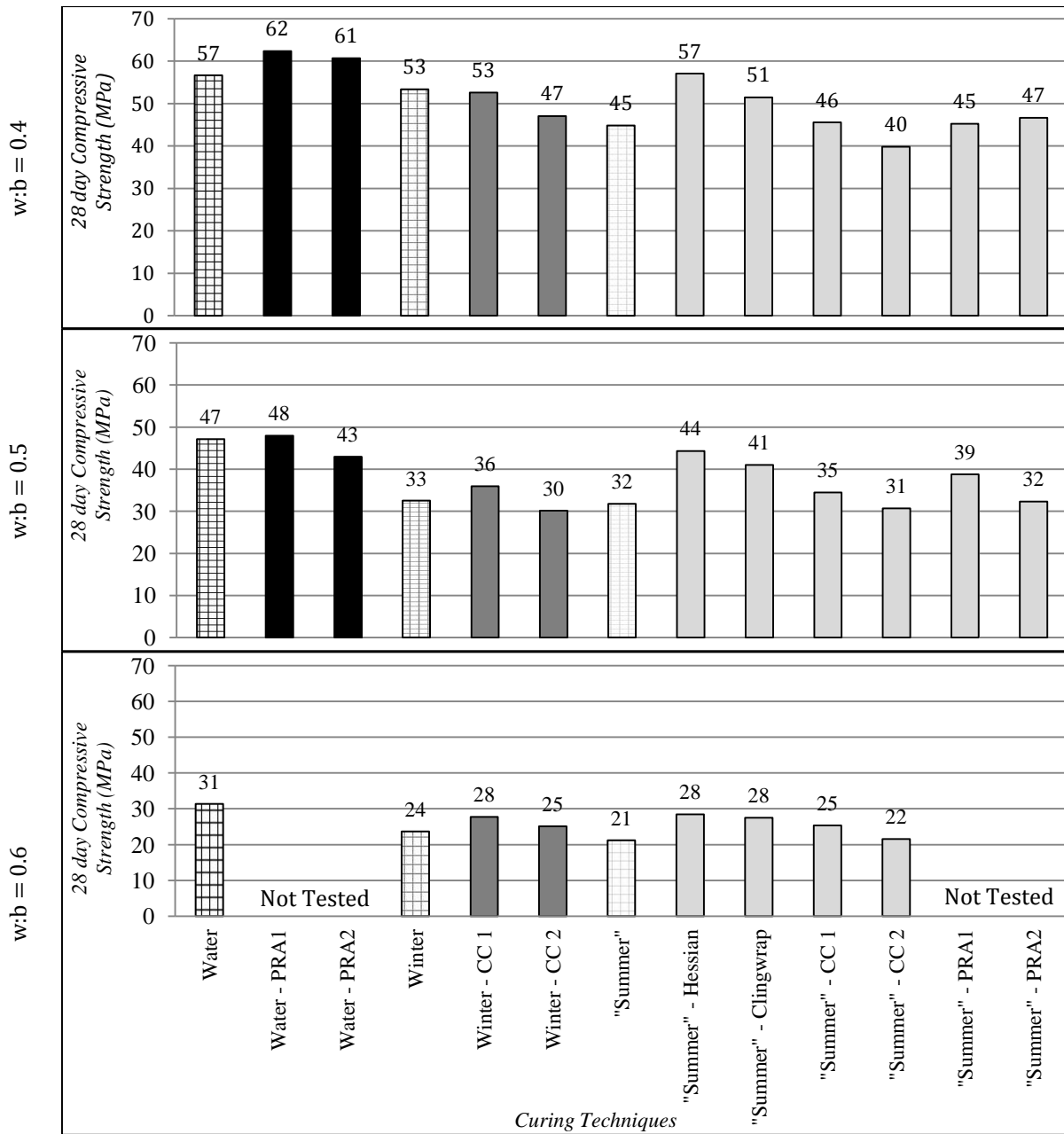


Figure 58: Comparison of  $f_c$  values obtained for 100% CEM I samples ( $w:b = 0.4, 0.5$  and  $0.6$ )

Table 22: Comparison of  $f_c$  values of each curing technique relative to the untreated reference samples (shaded value means curing method did not increase compressive strength relative to reference sample)

| Sample               | 100%<br>CEM I<br>w:b = 0.4 | 70% CEM I/<br>30% FA<br>w:b = 0.4 | 50% CEM I/<br>50% GGBS<br>w:b = 0.4 | 90% CEM I/<br>10% CSF<br>w:b = 0.4 | 100%<br>CEM I<br>w:b = 0.5 | 100%<br>CEM I<br>w:b = 0.6 |
|----------------------|----------------------------|-----------------------------------|-------------------------------------|------------------------------------|----------------------------|----------------------------|
| Water - Untreated    | 1                          | 1                                 | 1                                   | 1                                  | 1                          | 1                          |
| Water - PRA1         | 1.10                       | 0.95                              | 1.14                                | 1.12                               | 1.02                       |                            |
| Water - PRA2         | 1.07                       | 0.89                              | 1.15                                | 0.84                               | 0.91                       |                            |
| Winter - Untreated   | 1                          | 1                                 | 1                                   | 1                                  | 1                          | 1                          |
| Winter - CC1         | 0.99                       | 0.90                              | 1.04                                | 1.11                               | 1.11                       | 1.17                       |
| Winter - CC2         | 0.88                       | 0.71                              | 0.93                                | 1.03                               | 0.93                       | 1.06                       |
| "Summer" - Untreated | 1                          | 1                                 | 1                                   | 1                                  | 1                          | 1                          |
| "Summer" - Hessian   | 1.27                       | 1.61                              | 1.77                                | 1.07                               | 1.40                       | 1.34                       |
| "Summer" - Clingwrap | 1.15                       | 1.35                              | 1.70                                | 1.08                               | 1.29                       | 1.30                       |
| "Summer" - CC1       | 1.02                       | 1.18                              | 1.23                                | 1.07                               | 1.09                       | 1.19                       |
| "Summer" - CC2       | 0.89                       | 1.02                              | 1.04                                | 1.04                               | 0.97                       | 1.02                       |
| "Summer" - PRA1      | 1.01                       | 1.19                              | 1.37                                | 1.27                               | 1.22                       |                            |
| "Summer" - PRA2      | 1.04                       | 1.13                              | 1.14                                | 0.96                               | 1.02                       |                            |

### Influence of Curing Techniques

There was a notable difference between the results obtained for the water, winter and summer cured samples. Improved results were noted for the samples when higher levels of moisture were available for hydration during the curing period.

The inclusion of PRA2 marginally improved the durability properties in some cases, and had a negligible effect on others for both the water and "summer" cured samples. There is no evident trend present. The inclusion of PRA1 returned mixed results for the water cured samples but there was a general improvement in the "summer" cured samples. In some cases the admixtures improved the compressive strength obtained or had a negligible effect. It was also noted that in some cases the admixtures improved the compressive strength for the water cured samples but had no influence for the "summer" cured samples and vice versa.

CC1 obtained mixed results for the winter cured samples and generally improved the compressive strength of the "summer" cured samples. CC2 did not improve the compressive strength of any samples, although, in some instances, the results were negligibly improved compared to the relative reference sample.

The use of damp hessian and clingwrap as curing techniques resulted in improved compressive strength results for all samples with the hessian performing best of the two techniques. The use of the hessian was found to be significantly beneficial for the GGBS and FA samples relative to the untreated "summer" cured sample.

### *Influence of Binder Types*

The CEM I concrete samples obtained 70% of the highest results when comparing the effect of the binder types for the individual curing techniques. Conversely, the GGBS samples obtained 70% of the lowest values when comparing the effect of the binder types for the individual curing techniques. The CEM I and CSF samples were found to be less affected by curing techniques i.e. the difference noted between the highest and lowest values obtained was found to be lower than found for the FA and GGBS samples. The FA and GGBS samples were found to be significantly more sensitive to the curing techniques employed. More specifically, moist curing was found to be appreciably more beneficial. Khan et al. (1995) also observed that FA concretes are more susceptible to inadequate curing conditions than plain CEM I concrete. The untreated water cured GGBS sample obtained a lower result than expected, however, there is no in particular reason for this as the variation in the results obtained was negligible. The results obtained for the binder types when exposed to water curing were fairly similar, with no major trends being evident.

### *Influence of w:b Ratios*

The results obtained for the samples incorporating various w:b ratios were expected and in line with what has been observed in previous studies. The compressive strength values were found to decrease with increasing w:b ratio. This was found to be the case for each every sample when comparing w:b ratios for each curing technique in Figure 58.

### *Summary*

From the results presented above, it can be noted that improved compressive strength is obtained with adequate curing techniques. Higher levels and longer periods of moist curing significantly benefit the 28 day compressive strength obtained. In situations where adequate curing cannot be guaranteed, the use of lower w:b ratios and CEM I and CSF blend concretes is preferential as these are less susceptible to inadequate curing techniques.

Table 22 provides an easy reference as to which techniques were effective in improving the compressive strength relative to the reference samples. In instances where there is a marginal improvement or none at all, the values have been highlighted.

## **4.3. Durability Results**

### **4.3.1. Permeability (OPI and k)**

The results obtained for the permeability and OPI tests are presented below in Figure 59 and 60. Table 23 provides comparative results whereby each sample is presented as a proportion of its relative reference sample, indicated in bold. Each reference sample has been presented as a value of 1 and each treated sample as a proportion of it. Therefore, a value of lower than 1

depicts that the curing technique utilised has decreased the permeability obtained. The converse applies for values greater than 1. The OPI values were calculated using the permeability values (k) presented in Appendix E - Permeability Results (k).

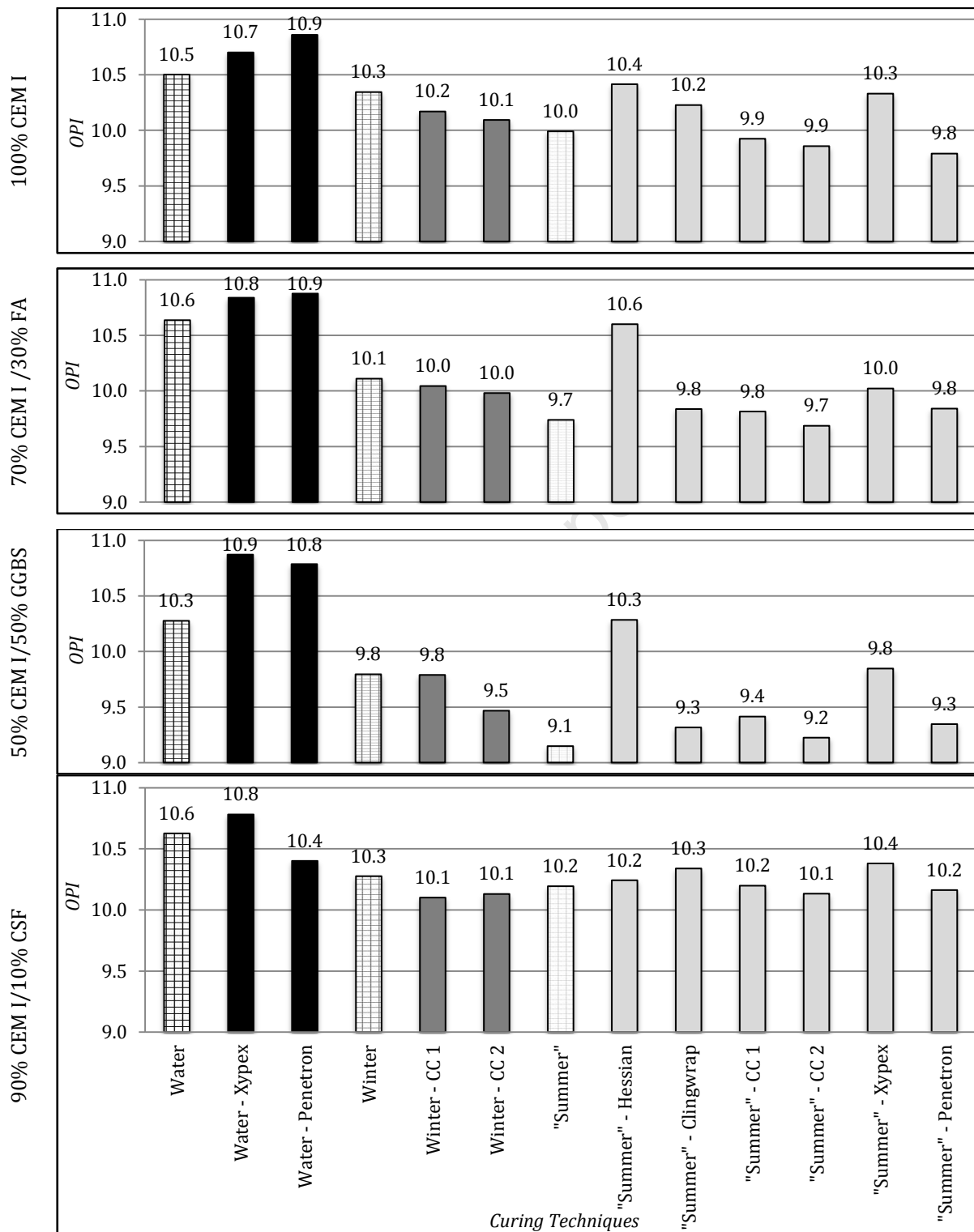


Figure 59: OPI values obtained comparing influence of curing technique and binder type (w:b = 0.4)

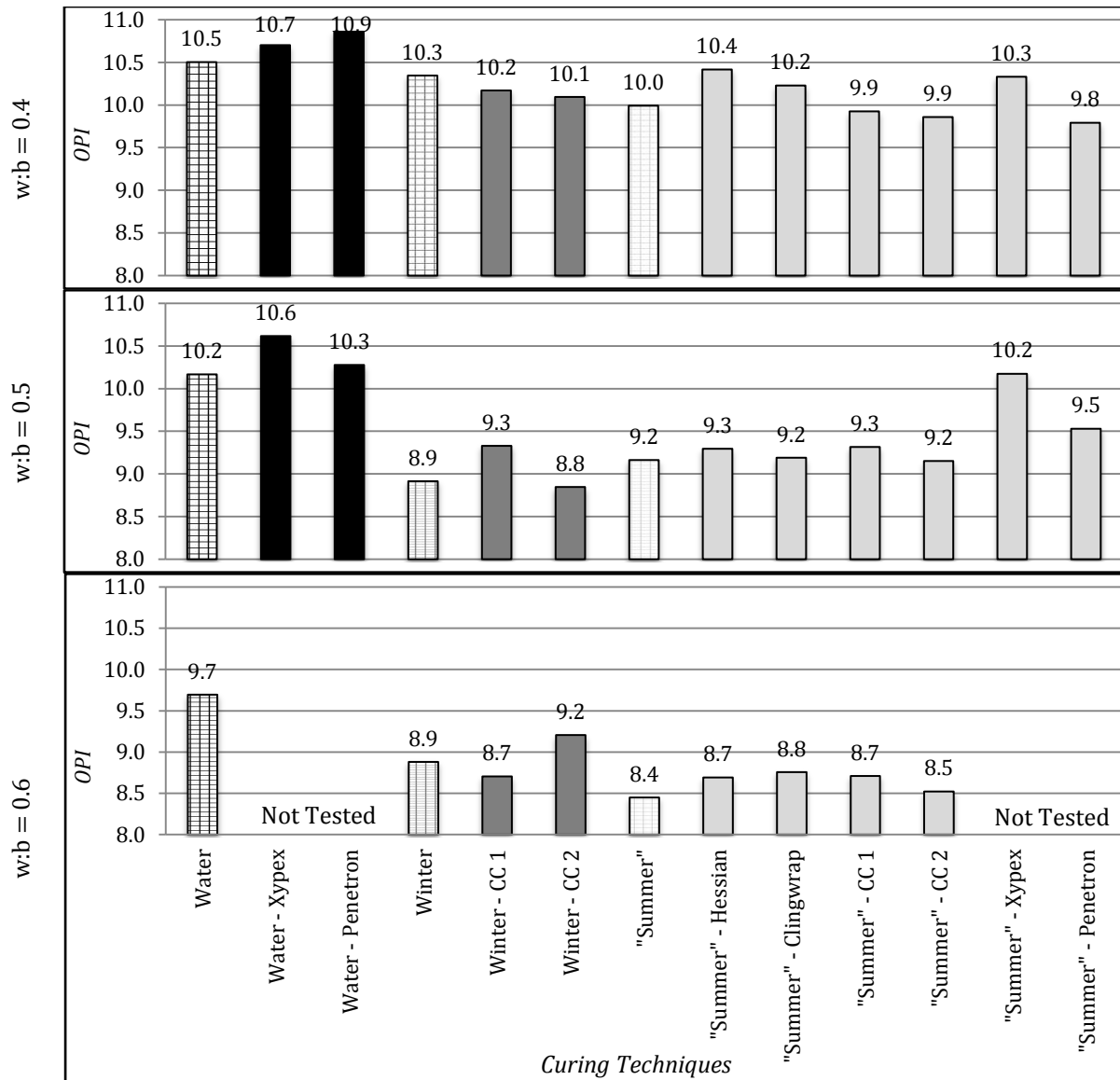


Figure 60: Comparison of OPI values obtained for 100% CEM I samples (w:b = 0.4, 0.5 and 0.6)

Table 23: Comparison of *k*-values of each curing technique relative to the untreated reference samples (shaded value means curing method did not decrease permeability relative to reference sample)

| Curing Technique     | 100% CEM I<br>w:b = 0.4 | 70% CEM I/<br>30% FA<br>w:b = 0.4 | 50% CEM I/<br>50% GGBS<br>w:b = 0.4 | 90% CEM I/<br>10% CSF<br>w:b = 0.4 | 100% CEM I<br>w:b = 0.5 | 100% CEM I<br>w:b = 0.6 |
|----------------------|-------------------------|-----------------------------------|-------------------------------------|------------------------------------|-------------------------|-------------------------|
| Water - Untreated    | 1                       | 1                                 | 1                                   | 1                                  | 1                       | 1                       |
| Water - PRA1         | 0.63                    | 0.63                              | 0.25                                | 0.70                               | 0.36                    |                         |
| Water - PRA2         | 0.44                    | 0.58                              | 0.31                                | 1.68                               | 0.78                    |                         |
| Winter - Untreated   | 1                       | 1                                 | 1                                   | 1                                  | 1                       | 1                       |
| Winter - CC1         | 1.50                    | 1.16                              | 1.01                                | 1.50                               | 0.38                    | 1.50                    |
| Winter - CC2         | 1.78                    | 1.35                              | 2.13                                | 1.40                               | 1.17                    | 0.47                    |
| "Summer" - Untreated | 1                       | 1                                 | 1                                   | 1                                  | 1                       | 1                       |
| "Summer" - Hessian   | 0.38                    | 0.14                              | 0.07                                | 0.89                               | 0.74                    | 0.57                    |
| "Summer" - Clingwrap | 0.58                    | 0.80                              | 0.68                                | 0.72                               | 0.94                    | 0.49                    |
| "Summer" - CC1       | 1.17                    | 0.84                              | 0.54                                | 0.99                               | 0.70                    | 0.55                    |
| "Summer" - CC2       | 1.36                    | 1.13                              | 0.84                                | 1.15                               | 1.03                    | 0.85                    |
| "Summer" - PRA1      | 0.46                    | 0.52                              | 0.20                                | 0.65                               | 0.10                    |                         |
| "Summer" - PRA2      | 1.59                    | 0.79                              | 0.63                                | 1.08                               | 0.43                    |                         |

### *Influence of Curing Techniques*

The permeability properties of the concrete samples obtained varied results as a result of the curing techniques implemented.

PRA2 decreased the permeability for the bulk of the water cured samples when compared to the untreated reference sample. However, mixed results were obtained for the uncured samples when compared to the untreated uncured samples indicating that continuous water supply is required for the material to be effective. PRA1 decreased the permeability when compared to both the untreated water and uncured samples. When comparing the effect of the crystallising PRA's, water and "summer" cured, with each of the corresponding reference samples, it can be seen that PRA1 was more effective in decreasing the permeability of the "summer" cured samples than it was in the water cured samples i.e. the permeability of the "summer" cured samples incorporating PRA1 was decreased more substantially compared to the untreated "summer" cured samples.

The use of curing compounds has generally negligible or slightly negative effects for both 'summer' and 'winter' environments for the lower w:b ratios. However, for the samples seemingly more sensitive to the curing techniques implemented, w:b = 0.6 and GGBS blend, the curing compounds decreased the permeability of the samples in the summer environment. This infers that the sealing effect of the curing compounds is beneficial in instances when concrete is particularly sensitive to the curing regime employed.

Hessian and clingwrap improved the impermeability of concrete samples for all binder types and w:b ratios compared to the untreated “summer” cured reference samples.

The samples left exposed to the winter environment achieved generally higher k-values than those of the hessian cured samples and comparable results to those of the clingwrap samples. It can therefore be inferred that the water in the hessian is more constant than that provided by winter precipitation, therefore hessian would prove more beneficial than simply leaving samples exposed to rain.

Results obtained by Krook (1995), Figure 16, concur with those obtained in this study. The only noticeable difference is that the plastic wrapped samples obtained higher OPI values than the hessian cured samples. The opposite is true of the results obtained in this study. This may be as a result of slight variations in how the hessian and plastic were utilised.

#### *Influence of Binder Types*

All of the water cured samples (w:b = 0.4), across the binder types, obtained comparable results with little difference between values obtained.

The permeability results obtained for the CEM I samples were similar to those obtained by the CSF samples. The CSF samples marginally influenced by curing technique implemented and were slightly less permeable for the summer cured samples. This is attributed to the fine filler effect of the finer CSF particles within the concrete matrix, leading to improved impermeability.

The use of FA and GGBS as SCM's results in concrete that is more susceptible to the curing techniques employed. The permeability values obtained for the FA and GGBS blended concrete samples were similar to the CEM I and CSF concretes when moist curing was employed. However, when moist curing was not implemented, the permeability obtained was drastically greater compared to the CEM I and CSF concretes.

The GGBS concrete samples were significantly influenced by curing technique implemented. The permeability is notably increased when excess water is not available for hydration.

#### *Influence of w:b Ratios*

The increase in w:b ratio results in increased permeability for all of the CEM I samples when comparing relative curing techniques. Increasing w:b ratio increases permeability as a result of increasing capillary porosity within the concrete matrix, a concept that is well documented and understood.

### *Summary*

From the results presented above, it can be noted that decreased permeability is obtained with adequate curing techniques. Higher levels and longer periods of moist curing significantly decrease the permeability of the concrete samples. This was seen for all binder types and for the range of w:b ratios for the CEM I mixes. It was noted that there was a decrease in OPI value with increasing w:b ratio. (Mackechnie, 1996), (Alexander, et al., 1999), (Ballim, et al., 2009), (Richardson, 2002)

Table 23 provides a reference as to which techniques were effective in decreasing the k-value relative to the reference samples. In instances where there is a marginal improvement, or none at all, the values have been highlighted.

The comparison of the effect of the binder types in each curing condition shows that the presence of SCM's do not ensure that improved durability properties will be inherent in the concrete. It was noted that the FA and GGBS samples are sensitive to different curing techniques, principally when there is a lack of excess moisture.

The CSF samples obtained higher values than all the other binder types, indicating that the CSF, in smaller percentages, may aid in decreasing the interconnectivity of the pore structure of the concrete due to its fine filler effect. The use of SCM's refines the pore structure of the concrete matrixes. The effect of higher percentages of CEM I replacement is reflected by the fact that the OPI results decrease with increasing CEM I replacement, 30 and 50% for the FA and GGBS respectively. (Alexander & Magee, 1999), (Khan & Ayers, 1995), (Ramezani pour & Malhotra, 1995)

The use of crystallising PRA's resulted in decreased permeability compared to untreated water and "summer" cured samples.

The curing compounds never sufficiently decreased the permeability of the cover layer to such a degree that there is clear evidence to suggest that the curing compounds adequately seal the concrete and prevent evaporation of the pore water. There was only a slight improvement for the GGBS samples, owing to their sensitivity to the warm and dry curing environment.

The use of hessian as a curing medium proved significantly beneficial in decreasing the permeability of the concrete samples compared to the untreated "summer" cured samples as well as the bulk of the winter cured samples.

In situations where adequate curing cannot be guaranteed, the use of lower w:b ratios and CEM I and CSF blend concretes is preferential as these are less susceptible to inadequate curing techniques.

### 4.3.2. Water Sorptivity Index (WSI)

The results obtained for the WSI tests are presented in Figure 61 and 62. Table 24 provides comparative results whereby each sample is presented as a proportion of its relative reference sample, indicated in bold. Each reference sample has been presented as a value of 1 and each treated sample as a proportion of it. Therefore, a value of lower than 1 depicts that the curing technique used has decreased the sorptivity obtained. The converse applies for values greater than 1.

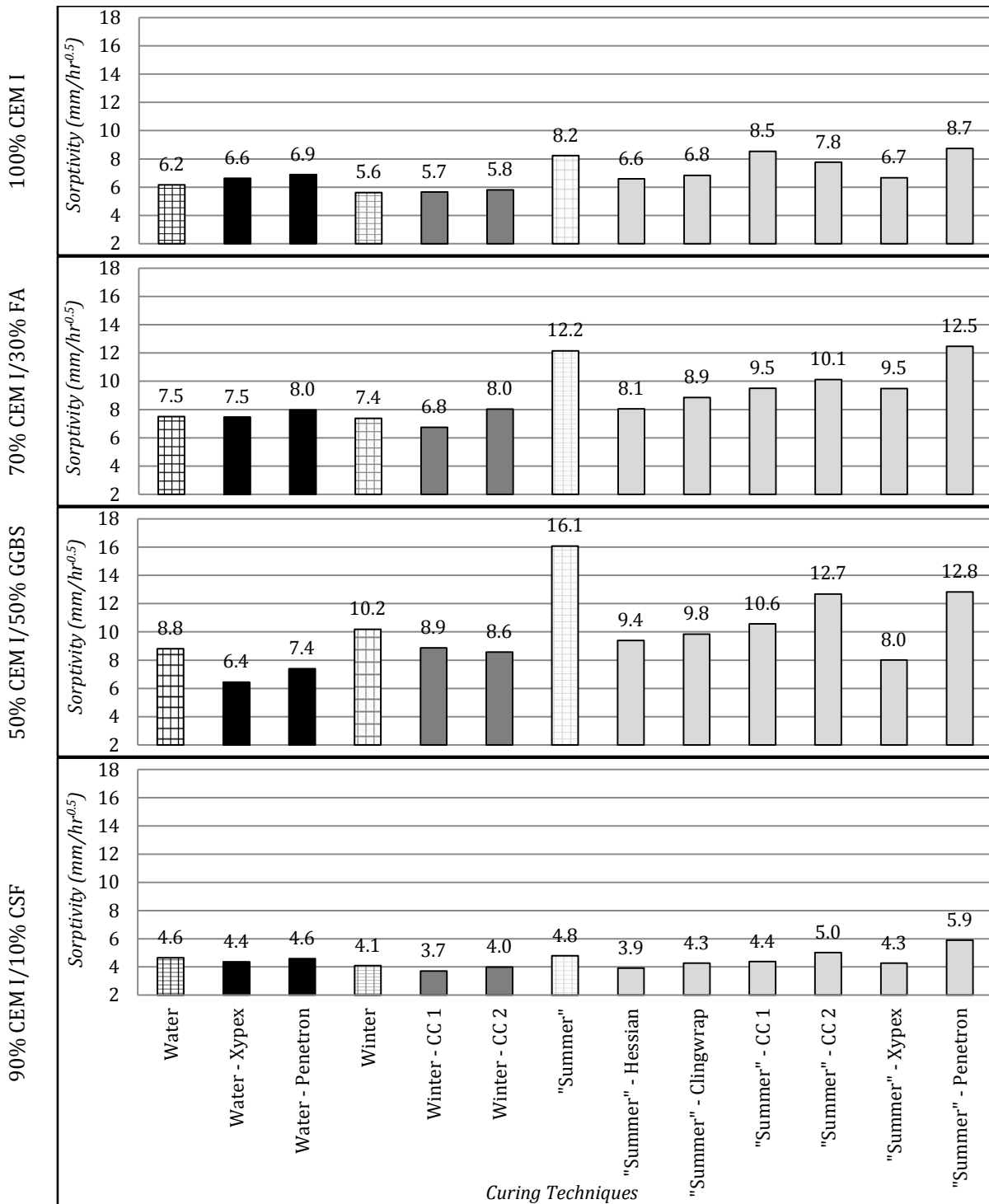


Figure 61: WSI values obtained comparing influence of curing technique and binder type (w:b = 0.4)

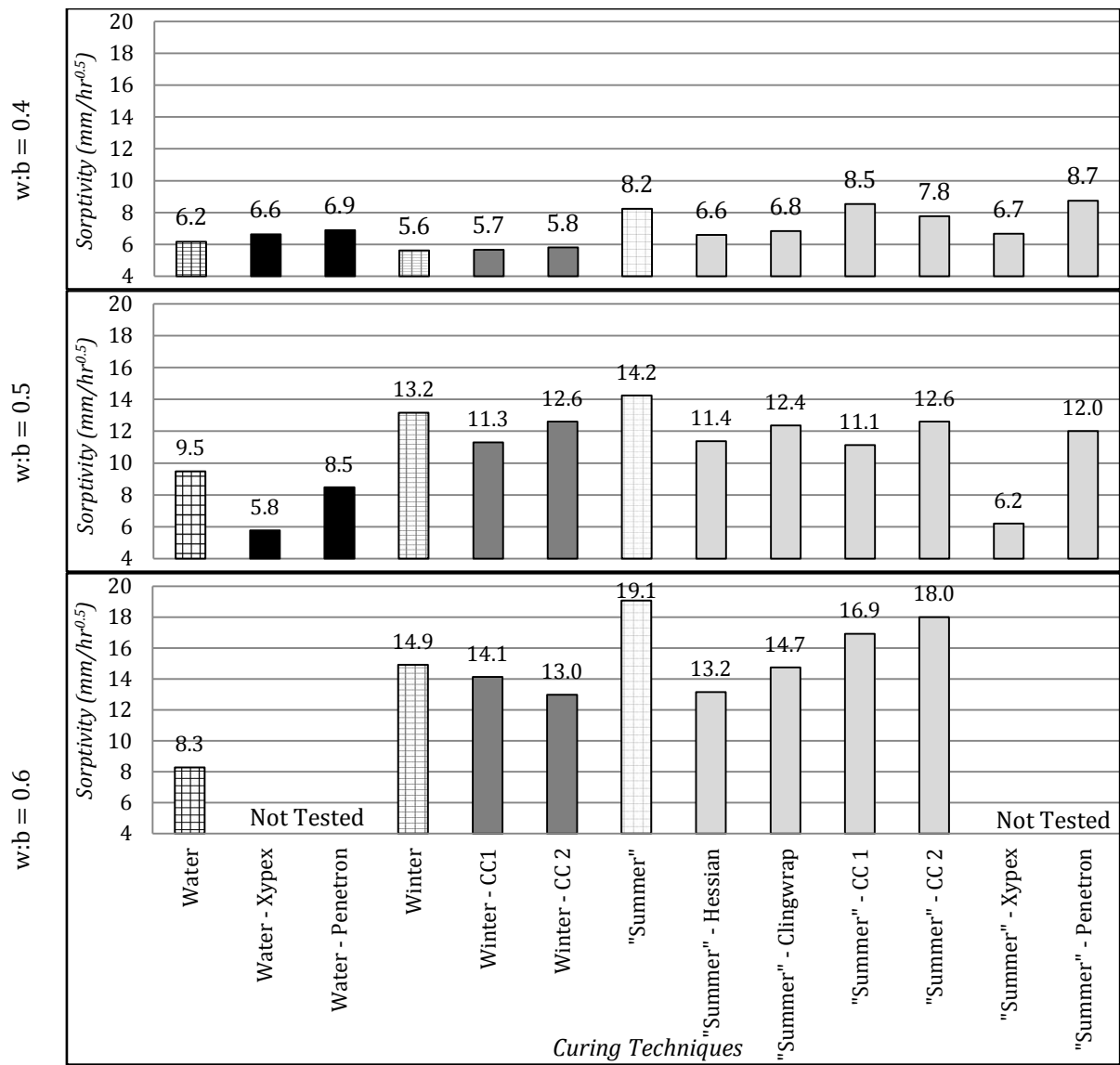


Figure 62: Comparison of WSI values obtained for 100% CEM I samples ( $w:b = 0.4, 0.5$  &  $0.6$ )

Table 24: Comparison of WSI values of each curing technique relative to the untreated reference samples (shaded value means curing method did not decrease sorptivity relative to reference sample)

| Curing Technique     | 100% CEM I | 70% CEM I/<br>30% FA | 50% CEM I/<br>50% GGBS | 90% CEM I/<br>10% CSF | 100% CEM I | 100% CEM I |
|----------------------|------------|----------------------|------------------------|-----------------------|------------|------------|
|                      | w:b = 0.4  |                      |                        |                       | w:b = 0.5  | w:b = 0.6  |
| Water - Untreated    | 1          | 1                    | 1                      | 1                     | 1          | 1          |
| Water - PRA1         | 1.08       | 1.00                 | 0.73                   | 0.94                  | 0.61       |            |
| Water - PRA2         | 1.12       | 1.06                 | 0.84                   | 0.99                  | 0.89       |            |
| Winter - Untreated   | 1          | 1                    | 1                      | 1                     | 1          | 1          |
| Winter - CC1         | 1.01       | 0.92                 | 0.87                   | 0.91                  | 0.86       | 0.95       |
| Winter - CC2         | 1.03       | 1.09                 | 0.84                   | 0.97                  | 0.96       | 0.87       |
| "Summer" - Untreated | 1          | 1                    | 1                      | 1                     | 1          | 1          |
| "Summer" - Hessian   | 0.80       | 0.66                 | 0.58                   | 0.82                  | 0.80       | 0.69       |
| "Summer" - Clingwrap | 0.83       | 0.73                 | 0.61                   | 0.89                  | 0.87       | 0.77       |
| "Summer" - CC1       | 1.04       | 0.78                 | 0.66                   | 0.91                  | 0.78       | 0.89       |
| "Summer" - CC2       | 0.94       | 0.83                 | 0.79                   | 1.05                  | 0.89       | 0.94       |
| "Summer" - PRA1      | 0.81       | 0.78                 | 0.50                   | 0.89                  | 0.44       |            |
| "Summer" - PRA2      | 1.06       | 1.03                 | 0.80                   | 1.23                  | 0.84       |            |

### Influence of Curing Techniques

The results obtained illustrate that there is a marginal difference between the results obtained for the samples (w:b = 0.4) when comparing the curing techniques. The results show that a lack of curing in the summer environment is extremely detrimental to the sorptivity properties and that moist curing is a requirement, especially for the FA and GGBS samples.

The use of the crystallising PRA's provided mixed results, in that there was no definitive trend as to the effectiveness of the products. The only definitive result was when PRA1 was used for all of the binder types in the "summer" environment, there was a decrease in the sorptivity values relative to the untreated "summer" cured samples.

The winter cured samples obtained lower sorptivity values than the water cured samples in some cases. The cases when the water cured samples performed better than the winter cured samples were for the samples seemingly more sensitive to the curing techniques employed i.e. the 0.4 GGBS and 0.5 and 0.6 CEM I samples.

The curing compounds decreased the sorptivity properties for the majority of the samples for both the winter and "summer" cured samples, although only marginally.

The hessian and clingwrap decreased the sorptivity values appreciably compared to the untreated "summer" samples for all binders and the various w:b ratios, as expected.

### *Influence of Binder Types*

The CSF samples obtained the lowest sorptivity values for all of the curing techniques when comparing the binder types. There was also a negligible difference between all of the values obtained for the CSF samples.

The GGBS samples generally obtained the highest values of the binder types for each curing technique. There was a large difference between the highest and lowest sorptivity values obtained, indicating the sensitivity of the GGBS concrete to the curing technique implemented. This was similarly noted, but to a lesser extent, for the FA samples.

The CEM I samples obtained marginally higher results compared to the CSF samples and, similarly, were seemingly less susceptible to the inadequate curing techniques.

### *Influence of w:b Ratio*

The results obtained for the various w:b ratios show that the sorptivity properties of the CEM I samples increases with increasing w:b ratios. The effect of the moist curing techniques becomes more evident with increasing w:b ratio. Moist curing significantly decreased the sorptivity when compared to the “summer” cured samples, with the 0.6 w:b ratio samples being the most considerably affected.

### *Summary*

The degree of initial curing affects the quality of the near surface concrete which in turn influences the sorptivity of the material. (Alexander, et al., 1999) From the above results, it can be seen that prolonged periods of moist curing improved the sorptivity properties of the concrete samples, for all binder types. It was noted that there was an increase in WSI value with increasing w:b ratio. (Ballim, et al., 2009)

Table 24 provides a reference as to which techniques were effective in decreasing the WSI value relative to the reference samples. In instances where there is a marginal improvement, or none at all, the values have been highlighted.

The comparison of the effect of the binder types in each curing condition shows that the use of CSF as an SCM is very beneficial in decreasing the sorptivity properties of the concrete samples. It was also marginally susceptible to a lack of moist curing, whereas the GGBS and FA samples were significantly so. The CEM I samples obtained similar results to the CSF samples. It can be noted that the replacement of CEM I in a mix design is only beneficial when done so with CSF.

The comparison of the curing techniques employed confirms that prolonged periods of moist curing are the most beneficial in improving the sorptivity properties of concrete. The crystallising PRA's did not conclusively decrease the sorptivity, except the PRA1 in the “summer” curing environment.

The use of damp hessian proved to generally be the most effective curing technique for the “summer” cured samples. The clingwrap cured samples obtained marginally higher results than the hessian cured samples and significantly lower results compared to the simulated “summer” cured samples.

The curing compounds were generally effective, more so for the concretes more sensitive to the curing conditions. These were the 0.4 GGBS and 0.5 and 0.6 CEM I samples. However, the hessian and clingwrap techniques were more beneficial than the curing compounds.

#### **4.3.3. Chloride Conductivity Index (CCI)**

The results obtained for the CCI tests conducted are presented below in Figure 63. Table 25 provides comparative results whereby each sample is presented as a proportion of its relative reference sample, indicated in bold. Each reference sample has been presented as a value of 1 and each treated sample as a proportion of it. Therefore, a value of lower than 1 depicts that the curing technique used has decreased the conductivity obtained. The converse applies for values greater than 1. The test is appropriate in giving an indication of the overall ionic transport process of concrete exposed to high ambient chloride concentrations. Low CCI values are indicative of a concrete’s resistance to ionic ingress. On the contrary, high CCI values are indicative of reduced resistance to chloride ion transport. (Mackechnie, 1996)

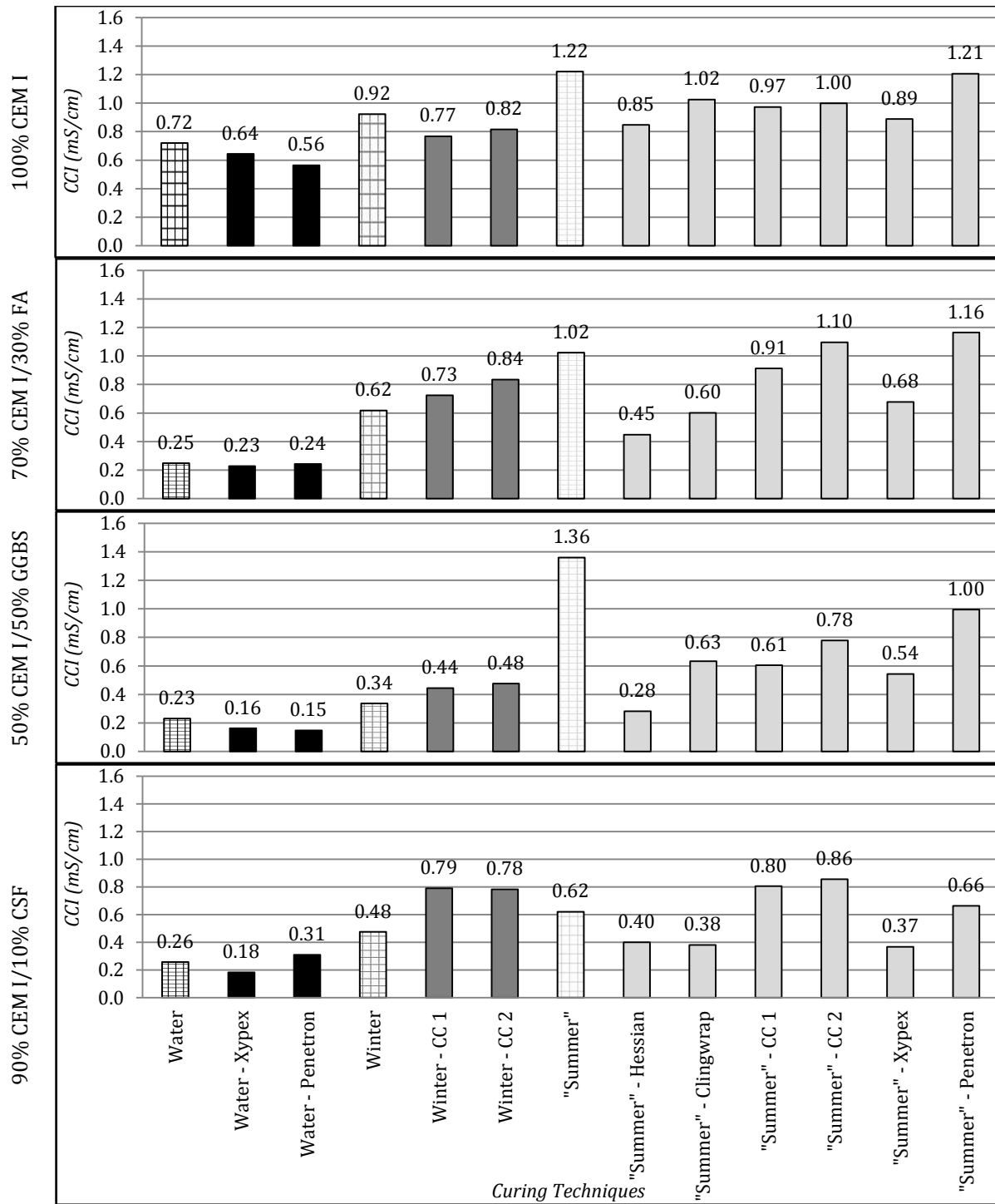


Figure 63: CCI values obtained comparing influence of curing technique and binder type ( $w:b = 0.4$ )

Table 25: Comparison of CCI-values of each curing technique relative to the untreated reference samples (shaded value means curing method did not decrease conductivity relative to reference sample)

| Curing Technique     | 100% CEM I | 70% CEM I/<br>30% FA | 50% CEM I/<br>50% GGBS | 90% CEM I/<br>10% CSF |
|----------------------|------------|----------------------|------------------------|-----------------------|
| Water - Untreated    | 1          | 1                    | 1                      | 1                     |
| Water - PRA1         | 0.89       | 0.92                 | 0.71                   | 0.71                  |
| Water - PRA2         | 0.78       | 0.98                 | 0.64                   | 1.20                  |
| Winter - Untreated   | 1          | 1                    | 1                      | 1                     |
| Winter - CC1         | 0.83       | 1.17                 | 1.32                   | 1.66                  |
| Winter - CC2         | 0.88       | 1.35                 | 1.42                   | 1.65                  |
| "Summer" - Untreated | 1          | 1                    | 1                      | 1                     |
| "Summer" - Hessian   | 0.69       | 0.44                 | 0.21                   | 0.64                  |
| "Summer" - Clingwrap | 0.84       | 0.59                 | 0.47                   | 0.61                  |
| "Summer" - CC1       | 0.80       | 0.89                 | 0.44                   | 1.30                  |
| "Summer" - CC2       | 0.82       | 1.07                 | 0.57                   | 1.38                  |
| "Summer" - PRA1      | 0.73       | 0.66                 | 0.40                   | 0.59                  |
| "Summer" - PRA2      | 0.99       | 1.14                 | 0.73                   | 1.07                  |

### *Influence of Curing Techniques*

The results obtained for the chloride conductivity tests performed illustrate that prolonged periods of moist curing results in the improved resistance to chloride ingress.

The inclusion of the crystallising PRA's provided varied results. PRA1 generally improved results for both the water and 'summer' cured samples. The improvement will more than likely have been as a result of the decrease in permeability of the samples due to the presence of the crystalline structure within the concrete matrix. A decrease in permeability was observed and discussed in Section 4.3.1. However, PRA2 was fairly ineffective.

The use of hessian and clingwrap as curing methods result in significantly improved CCI values when compared to the untreated "summer" cured samples for all binder types. The hessian cured samples generally performed the best of the curing techniques used in the "summer" environment. The hessian also resulted in lower CCI values when compared to the majority of the winter cured samples. It must be reiterated that the clingwrap and hessian were only applied for the first 7 days of curing and then exposed to the "summer" environment, highlighting the fact that the initial 7 days of curing are extremely important and that subsequent curing had little effect to CSF concrete.

The curing compounds were generally ineffective for the winter cured samples, but were found to be effective for most of the "summer" cured samples for all of the binders except the CSF samples, where they showed a negative effect.

### *Influence of Binder Types*

The inclusion of SCM's resulted in significantly lowered CCI values obtained for the majority of the samples when compared to the CEM I samples.

The GGBS samples obtained the majority of the lowest CCI values when comparing binder types for each curing technique, however, it obtained the highest CCI value of the binder types for the untreated “summer” sample. This, once again, indicates the sensitivity of the GGBS samples to the curing technique implemented and that some form of moist curing will significantly decrease the chloride conductivity.

The CEM I samples obtained the majority of the higher CCI values when comparing binder types for each curing technique.

### *Summary*

Table 25 provides a reference as to which techniques were effective in decreasing the CCI values relative to the reference samples. In instances where there is a marginal improvement, or none at all, the values have been highlighted.

The results obtained depict a trend whereby prolonged periods of moist curing result in a significantly vast improvement in the chloride resistance properties of the concrete samples.

The decrease in CCI values was more prevalent for the SCM blended concretes. The influence of binder type was seen with the blended mixes exhibiting lower values than the CEM I samples. Alexander et al. (1999) and Mackechnie (1996) both reported that the use of SCM's increases the resistance to chloride ingress.

The wet cured samples are further benefited by the presence of SCM's and greatly improve the resistance to chloride ingress. The GGBS samples performed best in all wet curing cases. However, this trend was not as evident for the air cured samples, as the evaporation of pore water in the low RH environment negatively effects the curing of the cover layer. CSF is shown in literature to have a generally lower resistance to chloride ingress than other SCM blends and plain CEM I cement concretes. The results obtained do not show a similar trend. It appears the presence of the CSF has lead to improved results and is perhaps less sensitive to low RH environments. Alexander et al. (1999) obtained similar findings, stating that “the lower sensitivity of CSF concrete to a lack of moist curing is clearly of significance.”

The positive effect of the SCM's, more specifically for the uncured cases, is more than likely due to the fine filler effect of the SCM's, which aid hydration by forming nucleation sites for the precipitation of hydration products. CSF reacts more rapidly, in comparison to GGBS, therefore the wet curing received by the dry-cured specimens may have allowed the CSF mixes to mature to a much greater extent. (Alexander & Magee, 1999)

Hessian resulted in only marginally higher CCI values than the untreated water cured sample for all binder types and significantly improved CCI values for the “summer” samples compared to the untreated “summer” cured samples.. It also resulted in improved results when compared

to the clingwrap cured samples, except for the CSF concrete, perhaps due to the low sensitivity of CSF to a lower RH.

The curing compounds were not generally effective for the winter cured samples, whereas, there was benefit in their use for the “summer” cured samples.

#### 4.4. Accelerated Carbonation

The accelerated carbonation test was performed to obtain the carbonation coefficients of the concretes. The carbonation depths obtained from the accelerated carbonation test were used to calculate the carbonation coefficients for the concretes.

##### 4.4.1. Carbonation Coefficient

The carbonation depths were calculated from an average obtained from each of the four samples of each mix design. The relationship between the depths obtained and the time taken for the reaction to occur enables the calculation of the carbonation coefficient. The carbonation coefficient was calculated using Equation 4, discussed earlier, and shown again below as Equation 8. (Richardson, 2002)

$$D = \frac{x}{t^{0.5}} \quad - \quad 8$$

The results obtained for the accelerated carbonation tests performed on each of the uncured samples is given in Figure 64. The plain CEM I samples obtained the lowest carbonation coefficients when compared to the samples incorporating the SCM's for w:b ratios of 0.4. The increase in carbonation coefficient with increasing w:b ratio observed for the plain CEM I samples is consistent with literature. (Salvoldi, 2010)

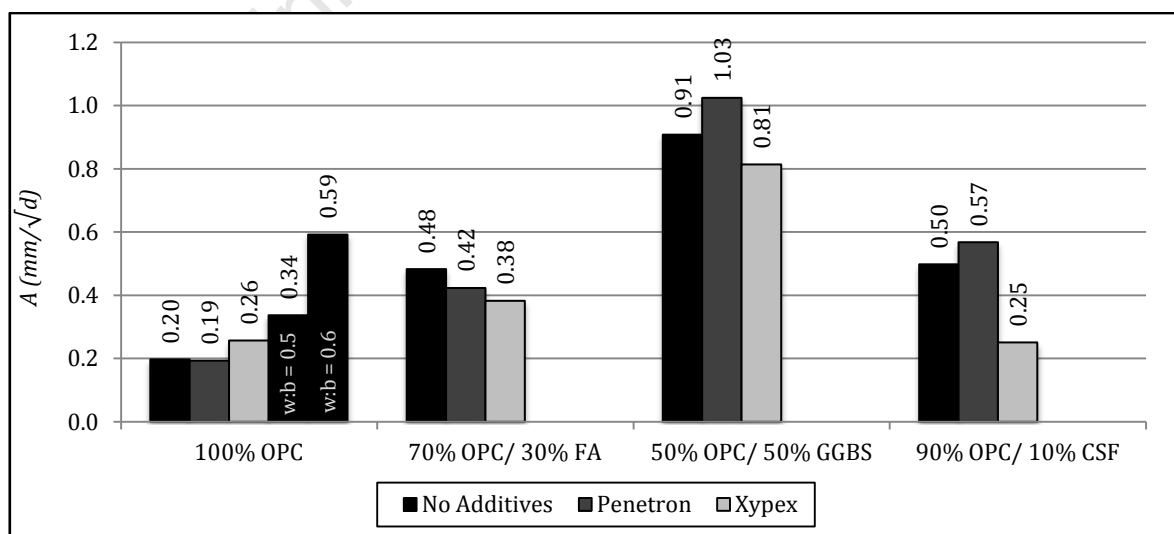


Figure 64: Carbonation coefficient (A) results (w:b = 0.4; unless otherwise specified)

The carbonation of concrete is influenced principally by the permeation of  $\text{CO}_2$  through the concrete, therefore, the permeability properties of the concrete influence carbonation. A correlation is thus expected between permeability and carbonation coefficients. Salvoldi (2010) found strong correlations for test samples. Figure 65, given below, illustrates the correlation between the carbonation coefficients and the corresponding permeability coefficients obtained for the untreated CEM I samples. A strong correlation is seen to exist between the two,  $R^2 = 0.96$ , further reinforcing results found in past literature. There is also a correlation found to exist between the compressive strength of the samples and the carbonation coefficient obtained, Figure 66. Similar results were also obtained by Khan et al. (2002)

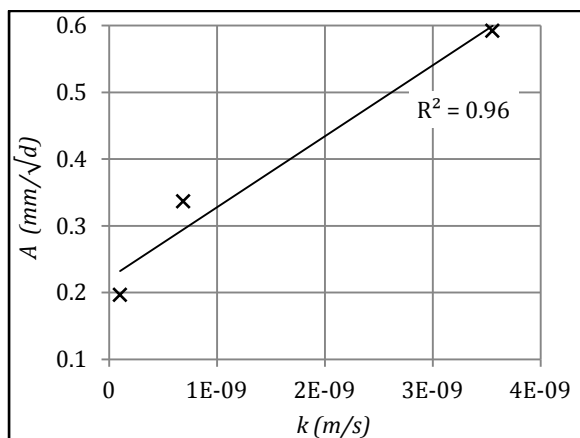


Figure 65: Carbonation coefficient ( $A$ ) vs. permeability ( $k$ ) for 100% CEM I samples

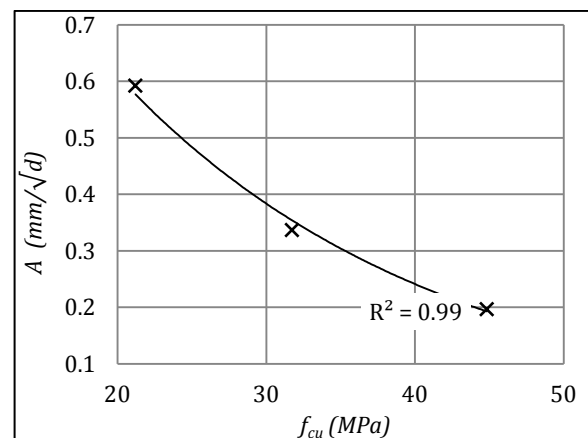


Figure 66: Carbonation coefficient ( $A$ ) vs. compressive strength ( $f_c$ ) for 100% CEM I samples

### Summary

Carbonation progression through concrete is affected to a large extent by the microstructure of the concrete, affected by the ability of  $\text{CO}_2$  to permeate into the concrete cover layer. The results obtained for the CEM I cement concretes showed a lower carbonation coefficient than the concretes containing the SCM's. This is expected as the presence of SCM's decreases the amount of carbonatable material in the concrete matrix and allows for a more rapid movement of the carbonation front. (Mackechnie & Alexander, 2002) The crystallising PRA's were added additionally and not as supplementary materials, therefore the amount of carbonatable material available in all samples, with same binder types, would not have changed. A decrease in the amount of carbonatable material would result in an increased carbonation coefficient.

Carbonation of concrete is affected by material, constructional and environmental factors. Effective curing of concrete is known to enhance the near-surface quality of concrete and is particularly important for fly ash and slag concrete. (Mackechnie & Alexander, 2002)

There is no definitive trend evident in the results obtained for the effects of the crystallising PRA's. What is more prevalent is the effect of the binders on the carbonation coefficient. The results depict that there is an increased rate of carbonation for all samples incorporating SCM's

when compared to the 100% CEM I sample. This is already well documented in literature. (Salvoldi, 2010)

## 4.5. Bulk Diffusion

The bulk diffusion test was conducted in order to establish the diffusion coefficients. The results are presented, firstly, as the chloride profiles for each sample. Secondly, the diffusion coefficients are presented in order to draw a comparison between curing techniques.

### 4.5.1. Chloride Concentrations

#### *Influence of curing technique*

The chloride concentration profiles for each of the untreated, PRA2 and PRA1 “Summer” cured samples are given in Figure 67 - 70. The results obtained for all of the samples were well below the threshold level, 0.4% by mass binder, prescribed by Mackechnie et al. (2001). All samples sufficiently resisted the ingress of chlorides satisfactorily. There is no clear trend as to the effects of the crystallising PRA's on the concrete's resistance to chloride ingress, as there is not a significant difference between the values obtained for each of the curing techniques. The figures illustrate that the untreated samples generally obtained similar chloride resistance properties when compared to the samples treated with crystallising PRA's.

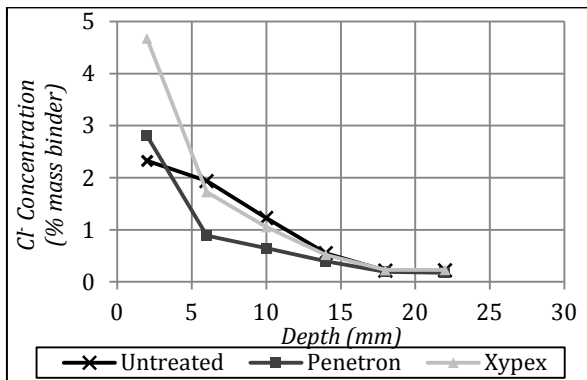


Figure 67: Cl<sup>-</sup> concentration profile for 100% CEM I samples

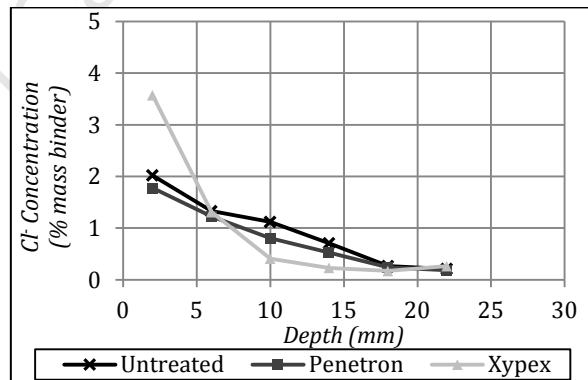


Figure 68: Cl<sup>-</sup> concentration profile for 70% CEM I/30% FA samples

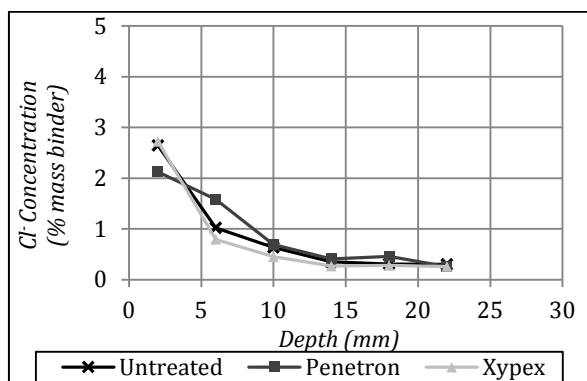


Figure 69: Cl<sup>-</sup> concentration profile for 50% CEM I/50% GGBS samples

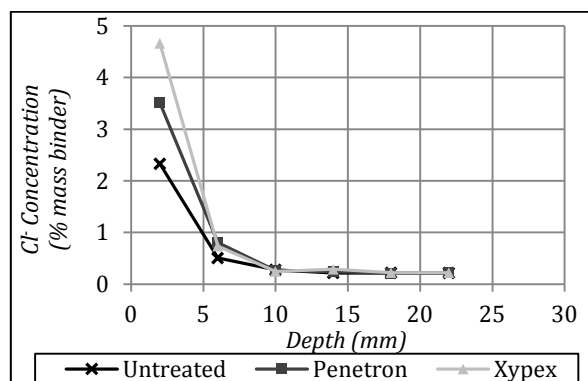


Figure 70: Cl<sup>-</sup> concentration profile for 90% CEM I/10% CSF samples

### *Influence of binder type*

Figure 71 - 73 present the chloride concentration profiles for each of the samples comparing the effect of binder type on the resistance to chloride ingress. Generally, the CSF and GGBS samples obtained improved results compared to the FA and CEM I samples.

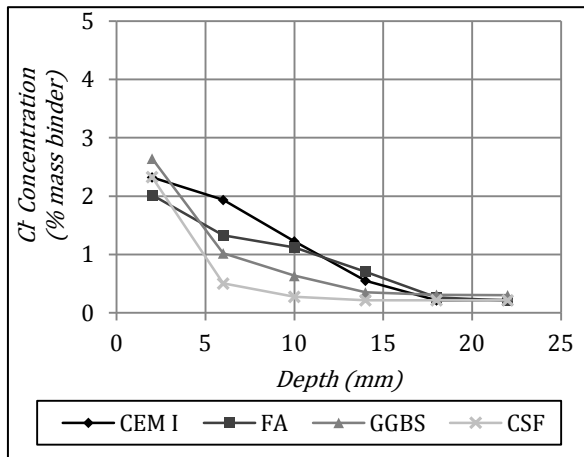


Figure 71:  $Cl^-$  concentration profile for untreated samples comparing binder types

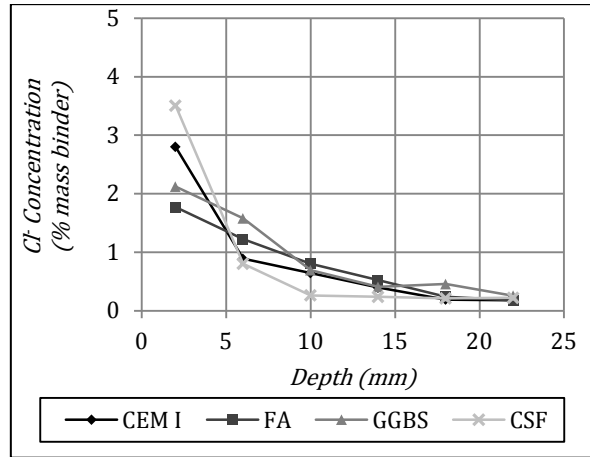


Figure 72:  $Cl^-$  concentration profile for PRA2 treated samples comparing binder types

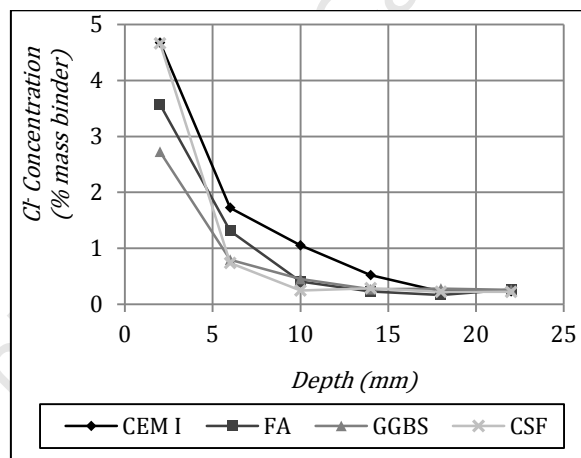


Figure 73:  $Cl^-$  concentration profile for PRA1 treated samples comparing binder types

### *Summary*

The chloride profiles presented above depict no discernible trend in the effects of the crystallising PRA's. The evaluation of results comparing binder types reveals that binder composition has a greater influence on the chloride resistivity properties of the concrete samples than the inclusion of the crystallising PRA's, for the tests conducted.

#### 4.6. Summary

A summary of the effects of the various curing techniques is given in Table 26 and for the 28 day compressive strength and DI tests. The table summarises whether or not each of the curing techniques were effective relative to each of the untreated reference samples. Table 27 relates the curing techniques to the untreated water cured sample in order to ascertain the effectiveness relative to moist curing.

The results reflect the significance of prolonged moist curing to the compressive strength and durability properties of the concrete samples tested. This is supported by the fact that the water cured samples achieved the best results for the compressive strength tests as well as the durability index tests. The observation is further supported by the fact that the hessian cured samples achieved the best results for the majority of the mix designs aside from the water cured samples.

The results obtained also confirm that the use of clingwrap is highly effective in negating the evaporation of the pore water, thereby aiding the development of the hydration products.

The use of the curing compounds was generally ineffective for the samples that were winter cured. This can be attributed to the sealing effect of the curing compounds preventing ambient moisture from aiding the hydration process.

CC2 was more effective in the “summer” environment compared to the equivalent winter cured samples, however, it achieved generally negative results when compared to the untreated “summer” cured samples. Conversely, CC1 achieved favourable results relative to the untreated “summer” sample. The improved results for CC1 illustrate that a somewhat effective seal was formed and partially prevented moisture loss from the cover layer of the concrete.

The crystallising PRA's provided similar results when applied to the water cured samples i.e. they generally resulted in improved properties. PRA1 was however more effective as it also improved the properties of the water cured CSF samples. The “summer” cured samples benefitted from the inclusion of PRA1, whereas the inclusion of PRA2 was only beneficial for the samples more sensitive to the curing methods employed i.e. the plain CEM I ( $w:b = 0.5$  and  $0.6$ ) and GGBS ( $w:b = 0.4$ ) samples. The use of PRA1 treated “summer” samples was generally only outperformed by the hessian cured “summer” samples, demonstrating that moist curing is more beneficial than simply adding a crystallising PRA and providing no further moist curing.

The results obtained reinforced the fact that an increase in  $w:b$  ratio results in a decrease in compressive strength and diminishes the durability properties. (Lydon, 1995), (Ballim, et al., 2009)

The influence of binder types varied with the curing technique implemented. The SCM samples incorporating GGBS were considerably more sensitive to the lack of moist curing and did not

improve the durability properties, except for the CCI values. The same was found with the samples incorporating FA, but to a lesser extent. The inclusion of GGBS and CSF improved the resistance to chloride ingress. The inclusion of the CSF was marginally beneficial due to the fine filler effect refining the pore structure of the concrete. The use of the SCM's lead to an increase of the carbonation coefficient of the concrete samples due to the decrease in carbonatable material available within the concrete matrix. (Salvoldi, 2010)

University of Cape Town

Table 26: Summary of effectiveness of curing techniques relative to their reference curing sample.

| Sample                  | 100% CEM I<br>(w:b = 0.4) |     |     |     | 100% CEM I<br>(w:b = 0.5) |     |     | 100% CEM I<br>(w:b = 0.6) |     |     | 70% CEM I/30% FA<br>(w:b = 0.4) |     |     |     | 50% CEM I/50% GGBS<br>(w:b = 0.4) |     |     |     | 90% CEM I/10% CSF<br>(w:b = 0.4) |     |     |     |   |
|-------------------------|---------------------------|-----|-----|-----|---------------------------|-----|-----|---------------------------|-----|-----|---------------------------------|-----|-----|-----|-----------------------------------|-----|-----|-----|----------------------------------|-----|-----|-----|---|
|                         | $f_c$                     | OPI | WSI | CCI | $f_c$                     | OPI | WSI | $f_c$                     | OPI | WSI | $f_c$                           | OPI | WSI | CCI | $f_c$                             | OPI | WSI | CCI | $f_c$                            | OPI | WSI | CCI |   |
| Water -<br>Untreated    | Reference                 |     |     |     | Reference                 |     |     | Reference                 |     |     | Reference                       |     |     |     | Reference                         |     |     |     | Reference                        |     |     |     |   |
| Water - PRA1            | ✓                         | ✓   | ✗   | ✓   | -                         | ✓   | ✓   | /                         | /   | /   | ✗                               | ✓   | ✗   | ✗   | ✓                                 | ✓   | ✓   | ✓   | ✓                                | ✓   | ✓   | ✓   | ✓ |
| Water - PRA2            | ✓                         | ✓   | ✗   | -   | ✗                         | ✓   | ✓   | /                         | /   | /   | ✗                               | ✓   | ✗   | ✗   | ✓                                 | ✓   | ✓   | ✓   | ✗                                | ✗   | -   | ✗   |   |
| Winter -<br>Untreated   | Reference                 |     |     |     | Reference                 |     |     | Reference                 |     |     | Reference                       |     |     |     | Reference                         |     |     |     | Reference                        |     |     |     |   |
| Winter - CC1            | -                         | ✗   | ✗   | ✓   | ✓                         | ✓   | ✓   | ✓                         | ✗   | -   | ✗                               | ✗   | ✓   | ✗   | -                                 | -   | ✓   | ✗   | ✓                                | ✗   | ✗   | ✗   |   |
| Winter - CC2            | ✗                         | ✗   | ✗   | ✓   | ✗                         | ✗   | -   | -                         | ✓   | ✓   | ✗                               | ✗   | ✗   | ✗   | ✗                                 | ✗   | ✓   | ✗   | -                                | ✗   | -   | ✗   |   |
| "Summer" -<br>Untreated | Reference                 |     |     |     | Reference                 |     |     | Reference                 |     |     | Reference                       |     |     |     | Reference                         |     |     |     | Reference                        |     |     |     |   |
| "Summer" -<br>Hessian   | ✓                         | ✓   | ✓   | ✓   | ✓                         | ✓   | ✓   | ✓                         | ✓   | ✓   | ✓                               | ✓   | ✓   | ✓   | ✓                                 | ✓   | ✓   | ✓   | ✓                                | ✓   | ✓   | ✓   |   |
| "Summer" -<br>Clingwrap | ✓                         | ✓   | ✓   | ✓   | ✓                         | ✓   | ✓   | ✓                         | ✓   | ✓   | ✓                               | ✓   | ✓   | ✓   | ✓                                 | ✓   | ✓   | ✓   | ✓                                | ✓   | ✓   | ✓   |   |
| "Summer" -<br>CC1       | -                         | ✗   | -   | ✓   | ✓                         | ✓   | ✓   | ✓                         | ✓   | ✓   | ✓                               | ✓   | ✓   | ✓   | ✓                                 | ✓   | ✓   | ✓   | ✓                                | -   | ✓   | ✗   |   |
| "Summer" -<br>CC2       | ✗                         | ✗   | -   | ✓   | ✗                         | -   | ✓   | -                         | ✓   | ✗   | -                               | -   | ✓   | -   | -                                 | ✓   | ✓   | ✓   | -                                | ✗   | -   | ✗   |   |
| "Summer" -<br>PRA1      | -                         | ✓   | ✓   | ✓   | ✓                         | ✓   | ✓   | /                         | /   | /   | ✓                               | ✓   | ✓   | ✓   | ✓                                 | ✓   | ✓   | ✓   | ✓                                | ✓   | ✓   | ✓   |   |
| "Summer" -<br>PRA2      | -                         | ✗   | -   | -   | -                         | ✓   | ✓   | /                         | /   | /   | ✓                               | ✓   | -   | ✗   | ✓                                 | ✓   | ✓   | ✓   | ✗                                | ✗   | ✗   | ✗   |   |

|   |           |   |                    |   |                 |   |                   |
|---|-----------|---|--------------------|---|-----------------|---|-------------------|
| ✓ | Effective | - | No apparent effect | ✗ | Negative effect | / | No test performed |
|---|-----------|---|--------------------|---|-----------------|---|-------------------|

Table 27: Summary of effectiveness of curing techniques relative to the untreated water cured sample.

| Sample             | 100% CEM I<br>(w:b = 0.4) |    |     |     | 100% CEM I (w:b<br>= 0.5) |    |     | 100% CEM I<br>(w:b = 0.6) |   |     | 70% CEM I/30% FA<br>(w:b = 0.4) |    |     |     | 50% CEM I/50% GGBS<br>(w:b = 0.4) |    |     |     | 90% CEM I/10% CSF<br>(w:b = 0.4) |    |     |     |
|--------------------|---------------------------|----|-----|-----|---------------------------|----|-----|---------------------------|---|-----|---------------------------------|----|-----|-----|-----------------------------------|----|-----|-----|----------------------------------|----|-----|-----|
|                    | f <sub>c</sub>            | k  | WSI | CCI | f <sub>c</sub>            | k  | WSI | f <sub>c</sub>            | k | WSI | f <sub>c</sub>                  | k  | WSI | CCI | f <sub>c</sub>                    | k  | WSI | CCI | f <sub>c</sub>                   | k  | WSI | CCI |
| Water-Untreated    | Reference                 |    |     |     | Reference                 |    |     | Reference                 |   |     | Reference                       |    |     |     | Reference                         |    |     |     | Reference                        |    |     |     |
| Water - PRA1       | ✓                         | ✓✓ | ×   | ✓✓  | -                         | ✓✓ | ✓✓  | /                         | / | /   | ×                               | ✓✓ | -   | ✓   | ✓                                 | ✓✓ | ✓✓  | ✓✓  | ✓                                | ✓✓ | ✓   | ✓✓  |
| Water - PRA2       | ✓                         | ✓✓ | ×   | ✓✓  | ×                         | ✓✓ | ✓   | /                         | / | /   | ×                               | ✓✓ | ×   | -   | ✓                                 | ✓✓ | ✓✓  | ✓✓  | ×                                | ×  | -   | ×   |
| Winter-Untreated   | ×                         | ×  | ✓   | ×   | ×                         | ×  | ×   | ×                         | × | ×   | ×                               | ×  | -   | ×   | ×                                 | ×  | ×   | ×   | ×                                | ×  | ✓   | ×   |
| Winter - CC1       | ×                         | ×  | ✓   | ×   | ×                         | ×  | ×   | ×                         | × | ×   | ×                               | ×  | ✓   | ×   | ×                                 | ×  | -   | ×   | ×                                | ×  | ✓   | ×   |
| Winter - CC2       | ×                         | ×  | ✓   | ×   | ×                         | ×  | ×   | ×                         | × | ×   | ×                               | ×  | ×   | ×   | ×                                 | ×  | -   | ×   | ×                                | ×  | ✓   | ×   |
| "Summer"-Untreated | ×                         | ×  | ×   | ×   | ×                         | ×  | ×   | ×                         | × | ×   | ×                               | ×  | ×   | ×   | ×                                 | ×  | ×   | ×   | ×                                | ×  | -   | ×   |
| "Summer"-Hessian   | -                         | ×  | ×   | ×   | ×                         | ×  | ×   | ×                         | × | ×   | ×                               | -  | ×   | ×   | ×                                 | -  | -   | ×   | ×                                | ×  | ✓   | ×   |
| "Summer"-Clingwrap | ×                         | ×  | ×   | ×   | ×                         | ×  | ×   | ×                         | × | ×   | ×                               | ×  | ×   | ×   | ×                                 | ×  | -   | ×   | ×                                | ×  | ✓   | ×   |
| "Summer"-CC1       | ×                         | ×  | ×   | ×   | ×                         | ×  | ×   | ×                         | × | ×   | ×                               | ×  | ×   | ×   | ×                                 | ×  | ×   | ×   | ×                                | ×  | ✓   | ×   |
| "Summer"-CC2       | ×                         | ×  | ×   | ×   | ×                         | ×  | ×   | ×                         | × | ×   | ×                               | ×  | ×   | ×   | ×                                 | ×  | ×   | ×   | ×                                | ×  | -   | ×   |
| "Summer"-PRA1      | ×                         | ×  | ×   | ×   | ×                         | -  | ✓✓  | /                         | / | /   | ×                               | ×  | ×   | ×   | ×                                 | ×  | ✓   | ×   | ×                                | ×  | ✓   | ×   |
| "Summer"-PRA2      | ×                         | ×  | ×   | ×   | ×                         | ×  | ×   | /                         | / | /   | ×                               | ×  | ×   | ×   | ×                                 | ×  | ×   | ×   | ×                                | ×  | ×   | ×   |

|    |           |   |                      |   |                    |   |                 |   |                   |
|----|-----------|---|----------------------|---|--------------------|---|-----------------|---|-------------------|
| ✓✓ | Effective | ✓ | Marginally effective | - | No apparent effect | × | Negative effect | / | No test performed |
|----|-----------|---|----------------------|---|--------------------|---|-----------------|---|-------------------|

The curing techniques are ranked, Table 28, with respect to  $f_c$ , OPI and CCI. The rankings are given separately as the curing techniques may be beneficial in environment specific situations, thus certain methods may be applicable. The curing techniques are sorted by exposure environment in order to practically ascertain the best method to implement in a given setting. In a dry summer environment, curing is essential, preferably moist. Whereas, for a wet winter, as found in the Western Cape, it may be prudent to protect the concrete, however, no specialist curing may be required. Each curing technique is listed in descending order of performance:

*Table 28: Ranking of curing techniques with respect to  $f_c$ , OPI and CCI*

| Winter |           |           |           |
|--------|-----------|-----------|-----------|
|        | $f_c$     | OPI       | CCI       |
| 1      | CC1       | Untreated | Untreated |
| 2      | Untreated | CC1       | CC1       |
| 3      | CC2       | CC2       | CC2       |
| Summer |           |           |           |
|        | $f_c$     | OPI       | CCI       |
| 1      | Hessian   | PRA1      | Hessian   |
| 2      | Clingwrap | Hessian   | PRA1      |
| 3      | PRA1      | Clingwrap | Clingwrap |
| 4      | CC1       | CC1       | CC1       |
| 5      | PRA2      | PRA2      | Untreated |
| 6      | CC2       | Untreated | CC2       |
| 7      | Untreated | CC2       | PRA2      |

The rankings illustrate that prolonged periods of moist curing are far more beneficial to the durability properties of the concrete samples. The expected variations due to binder type and w:b ratio were obtained and expected. The results obtained for the crystallising PRA's and curing compounds were less expected due to the proprietary nature of the products utilised and the differences between similar products used in previous studies.

## CHAPTER FIVE

### 5. Conclusions and Recommendations

#### 5.1. Curing Techniques

##### 5.1.1. Water Curing

The results confirmed that prolonged water curing is the most beneficial method in ensuring the highest level of durability for concrete. (Spears, 1983) Moist curing is most beneficial for samples incorporating SCM's. Although full immersion of concrete elements is not practical, other methods of moist curing may be applied and may be, nearly, equally beneficial. Ponding, sprinkling and fogging are other methods that may be utilised.

##### 5.1.2. Hessian

The use of hessian as a curing technique, in the "summer" environment, resulted in considerably improved compressive strength and durability index results for the majority of the binder types and w:b ratios. It obtained the best results of the samples not water cured. It proved most beneficial for the concrete mixes more sensitive to the curing technique employed; the FA and GGBS (w:b = 0.4) and CEM I (w:b = 0.5 and 0.6) samples. The hessian was only applied for the initial 7 days and then exposed to a simulated "summer" environment. It could also be applied in winter conditions as it would provide a more consistent source of external moisture during the initial curing period, this is also considering the fact that the hessian cured summer samples obtained generally better durability results than all the winter cured samples. Prolonged use of hessian would also prove more beneficial.

##### 5.1.3. Clingwrap

The use of Clingwrap as a curing technique provides very good results for all binder types and for the three w:b ratios of the plain CEM I cement concretes. When compared to the full water cured samples, it proved to be an adequate alternative, especially considering the clingwrap was only applied for the first 7 days and then placed in a simulated "summer" environment. The method helps prevent the evaporation of pore water from the cover layer of the concrete, aiding hydration. It was, however, not as effective as damp hessian.

##### 5.1.4. Winter

The samples left exposed to the winter environment obtained poorer durability properties than obtained by the water and hessian cured samples. The samples with the lower w:b ratios (0.5 and 0.6) achieved DI values that were predominantly outside of the DI limits recommended by SANRAL (SANRAL, 2009) and, hence, should not be used in extreme exposure conditions where durable concrete is required i.e. lower w:b ratios must be specified. The results obtained show

that it is better to leave concrete untreated in winter, in the Western Cape, provided that involves cool and wet conditions, than to apply a curing compound. However, the cool and wet conditions in the winter environment provided for improved durability properties when compared to the untreated “summer” cured samples.

#### 5.1.5. “Summer” (Controlled Environment)

The “summer” cured samples served to illustrate that a lack of excess moisture during curing would detrimentally affect the durability properties of the concrete samples. The tests conducted displayed this fact. Concrete elements should ideally not be left untreated and exposed to warm and dry conditions. Ideally, concrete should never be left exposed to warm and dry conditions. Table 28 illustrated that hessian, clingwrap and the inclusion of PRA1 in the concrete improved the durability properties of the “summer” exposed samples.

#### 5.1.6. Curing Compounds

The use of curing compounds obtained mixed results for the compressive strength and the DI tests. No clear trend was prevalent in determining the sealing abilities of the curing compounds. The winter and “summer” samples should have achieved comparable results should an absolute seal have been formed, preventing moisture loss. This was however not the case.

The use of the curing compounds rarely sufficiently sealed the concrete samples in the controlled uncured environment and therefore did not negate the loss of moisture to evaporation from the cover layer. CC1 generally improved the durability properties, whereas CC2 had little effect in the “summer” environment.

The curing compounds also did not improve the durability properties of the concrete samples in the winter environment compared to the untreated sample. The partial sealing effect of the compounds inhibited the ingress of excess environmental moisture into the cover layer, thereby hindering the hydration process within the cover layer. It is therefore not advisable to make use of curing compounds when precipitation is prevalent in the area of concern.

##### 1. CC1 (Solvent based)

The use of CC1 resulted in a general improvement of the durability properties of the concrete samples. CC1 was generally more beneficial for the samples that were more sensitive to environmental factors, these were the CEM I samples (w:b = 0.5 and 0.6) and the samples incorporating FA and GGBS (w:b = 0.4).

## 2. CC2 (Liquid emulsified paraffin wax)

CC2 was generally ineffective. It obtained generally mixed results and was largely only beneficial for the samples incorporating GGBS (w:b = 0.4) in the summer environment.

## 5.2. Durability Enhancers

### 5.2.1. Crystallising PRA's

The inclusion of the crystallising PRA's had varying effects due to the proprietary nature and dosages of the respective products.

The use of CSF as an SCM was found to be generally more favourable to the durability properties of the untreated "summer" cured samples than the CEM I, FA and GGBS samples incorporating crystallising PRA's cured in the "summer" environment. Therefore, the inclusion of CSF may be more beneficial than the inclusion of crystallising PRA's. However, the crystallising PRA's were found to provide favourable results for the mixes seemingly more sensitive to the "summer" curing environment i.e. the FA and GGBS samples (w:b = 0.4) and the CEM I samples (w:b = 0.5)

The general conclusion is that the crystallising PRA's will be beneficial in situations where some form of moist curing is implemented, lower w:b ratios are specified and GGBS and FA are utilised in the mix design. These results agree with those obtained by the ACI Committee 212 (2010), Figure 18 and 19, that the crystallising PRA's decrease the permeability of FA concrete.

#### *PRA1*

The inclusion of PRA1 as a durability enhancer tended to improve the durability properties for both the water and "summer" cured samples. It was generally more beneficial for the "summer" cured samples and may be as a result of both the crystallisation of the product and the fine filler effect refining the pore structure of the concrete. This observation is drawn from the comparison of the PRA1 treated samples to the untreated "summer" cured samples.

#### *PRA2*

The inclusion of PRA2 was less effective than PRA1. However, a lower dosage was used as per manufactures recommendations. It was found to be generally ineffective in situations where excess moisture is not available for hydration of the material.

## 5.3. Binder Types

Binder type proved to be particularly important to the durability properties achieved. The influence of binder types varies with the curing technique implemented. The inclusion of FA and

GGBS proved to detrimentally affect the durability properties of the samples that were exposed to the summer environment. The inclusion of CSF was particularly beneficial regardless of the curing technique employed and similar results were obtained for all curing techniques for the OPI and WSI values. This was less so for the CCI values.

The inclusion of the SCM's results in increased rates of carbonation due to the decrease in carbonatable material. It is therefore not advised to use SCM's in situations where a high CO<sub>2</sub> concentration may be encountered. (Salvoldi, 2010)

#### 5.4. w:b Ratios

The results obtained were expected and further support the fact that lower w:b ratios lead to an improvement of the durability properties of concrete. Tests were only conducted on CEM I samples. However, similar conclusions have been found with other binder types in past studies. (Alexander, et al., 1999)

#### 5.5. Application of Findings

Table 28, discussed above, ranked the curing techniques relative to one another. However, it fails to consider the effectiveness of each of the techniques. Table 29 and 28 summarise the practicality of implementing the tested curing techniques in the "summer" and winter environments i.e. implementation is indicated to be either viable or ineffective in the summer or winter environment.

Table 29: Feasibility of curing techniques in warm and dry "Summer" environment

| Curing Technique | Summer |     |     |
|------------------|--------|-----|-----|
|                  | $f'_c$ | OPI | CCI |
| Untreated        | x      | x   | x   |
| Hessian          | ✓      | ✓   | ✓   |
| Clingwrap        | ✓      | ✓   | ✓   |
| CC1              | ✓      | ✓   | ✓   |
| CC2              | x      | x   | ✓   |
| PRA1             | ✓      | ✓   | ✓   |
| PRA2             | x      | ✓   | x   |

Table 30: Feasibility of curing techniques in cool and wet Winter environment

| Curing Technique | Winter |     |     |
|------------------|--------|-----|-----|
|                  | $f'_c$ | OPI | CCI |
| Untreated        | ✓      | ✓   | ✓   |
| CC1              | x      | x   | x   |
| CC2              | x      | x   | x   |

|   |           |   |             |
|---|-----------|---|-------------|
| ✓ | Effective | x | Ineffective |
|---|-----------|---|-------------|

## 5.6. Conclusions

The results of the study allow for the following conclusions to be drawn:

- i. Fully immersed water curing imparted the best durability properties on the concrete samples, it is however extremely impractical to implement and is therefore not an option to industry.
- ii. Damp hessian proved to be the most effective moist curing technique considering that full immersion is impractical, and helped obtain the best durability properties of all the curing techniques tested.
- iii. Clingwrap, applied for 7 days immediately after demoulding, proved to be an effective method of sealing the concrete surface and preventing the evaporation of pore water, thereby aiding in the hydration of the cover layer.
- iv. The winter cured samples obtained fairly high DI values when untreated. This is due to the high amount of precipitation prevalent in the Cape Town area during winter. Although only two curing compounds were tested on the winter samples, it can be seen that sealing methods were not of benefit to the concrete samples. Hessian curing would be more beneficial as it provides a more constant source of external moisture to the concrete cover layer.
- v. The utilisation of the curing compounds gave mixed results. Neither compound was effective for the winter cured samples. This was expected as the sealing effect of the compounds would have prevented excess moisture from entering the cover layer of the concrete. CC1 proved to be effective in improving the durability properties of the more sensitive concrete samples exposed to the summer environment i.e. the GGBS, FA (w:b = 0.4) and the CEM I (w:b = 0.5 and 0.6) samples. CC2 proved to be generally ineffective.

Use of the curing compounds could be beneficial in cases where methods of curing, such as hessian or clingwrap, cannot be implemented. i.e. the undersides of slabs or beams etc.

- vi. The use of the crystallising PRA's as durability enhancers provided mixed results. The inclusion of PRA1 in the concrete provided improved durability properties for all samples. The use of PRA2, however, generally resulted in no marked improvement from the reference samples.

As crystallising PRA's require water for hydration, as illustrated by the generally improved results obtained for the water cured samples, employment may be more advantageous when used in conjunction with some form of moist curing or when a water retaining structure is the element in question.

## 5.7. Recommendations for Further Study

### *Mix design*

Further experimental work should be conducted, taking into consideration the various properties of the materials currently available to industry. Various improvements in mix designs could further improve the durability properties of concrete specimens. Factors such as aggregate types and quantities, variations in SCM proportions and a wider range of w:b ratios could be examined.

### *Alternative curing methods*

There exist considerably more curing techniques than those discussed in the preceding study. Current techniques include forms left in place, fogging, microwave, steam, electrical, oil, infrared, insulating blankets and integral polymers. These curing methods, some of them fairly new, are not readily used in South Africa. It is therefore prudent to investigate the effect of the more practical methods, whilst considering the nature of the South African construction environment, on the durability properties of concrete.

### *Combinations of curing techniques*

Each of the curing techniques tested, as well as those discussed immediately above, are not exclusive practices. A combination of any of these may be practically and economically viable.

The following options are worth investigating:

- wetted concrete surface sealed with clingwrap or plastic
- wetted hessian sealed in clingwrap or plastic
- wetted hessian, for first 7 days, exposed to ambient precipitation
- crystallising PRA's utilised in samples to be moist cured i.e. hessian or ponded concrete surfaces or those exposed to high levels of ambient precipitation

### *On-site testing*

Concrete curing on site is far more variable than curing procedures in a controlled laboratory environment. Although previous studies have been conducted, Krook (1995), modern curing technologies need to be accounted for. Testing on site may aid in the implementation of standards for curing practices in South Africa.

*Investigation into ingress of deleterious substances*

The ingress of deleterious substances was examined in brief in this study. A more in depth analysis of the effects of curing on the rate of carbonation and chloride diffusion needs to be undertaken. Long term testing may be beneficial in determining the long term effects of curing.

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**APPENDICES**

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## Appendix A - Climatic Data

*Table 31: Environmental Data for Cape Town, South Africa (South African Weather Service, n.d.)*

| Month | Temperature (°C) |                       |                       |                 | Precipitation        |                               |
|-------|------------------|-----------------------|-----------------------|-----------------|----------------------|-------------------------------|
|       | Highest Recorded | Average Daily Maximum | Average Daily Minimum | Lowest Recorded | Average Monthly (mm) | Highest 24 Hour Rainfall (mm) |
| Jan   | 39               | 26                    | 16                    | 7               | 15                   | 41                            |
| Feb   | 38               | 27                    | 16                    | 6               | 17                   | 27                            |
| March | 41               | 25                    | 14                    | 5               | 20                   | 42                            |
| April | 39               | 23                    | 12                    | 2               | 41                   | 39                            |
| May   | 34               | 20                    | 9                     | 1               | 69                   | 65                            |
| June  | 30               | 18                    | 8                     | -1              | 93                   | 58                            |
| July  | 29               | 18                    | 7                     | -1              | 82                   | 61                            |
| Aug   | 32               | 18                    | 8                     | 0               | 77                   | 56                            |
| Sep   | 33               | 19                    | 9                     | 0               | 40                   | 29                            |
| Oct   | 37               | 21                    | 11                    | 1               | 30                   | 53                            |
| Nov   | 40               | 24                    | 13                    | 4               | 14                   | 30                            |
| Dec   | 35               | 25                    | 15                    | 6               | 17                   | 21                            |
| Year  | 41               | 22                    | 11                    | -1              | 515                  | 65                            |

*Table 32: Environmental Data for Johannesburg, South Africa (South African Weather Service, n.d.)*

| Month | Temperature (°C) |                       |                       |                 | Precipitation        |                               |
|-------|------------------|-----------------------|-----------------------|-----------------|----------------------|-------------------------------|
|       | Highest Recorded | Average Daily Maximum | Average Daily Minimum | Lowest Recorded | Average Monthly (mm) | Highest 24 Hour Rainfall (mm) |
| Jan   | 35               | 26                    | 15                    | 7               | 125                  | 188                           |
| Feb   | 34               | 25                    | 14                    | 6               | 90                   | 56                            |
| March | 32               | 24                    | 13                    | 2               | 91                   | 92                            |
| April | 29               | 21                    | 10                    | 1               | 54                   | 50                            |
| May   | 26               | 19                    | 7                     | -3              | 13                   | 70                            |
| June  | 23               | 16                    | 4                     | -8              | 9                    | 31                            |
| July  | 24               | 17                    | 4                     | -5              | 4                    | 17                            |
| Aug   | 26               | 19                    | 6                     | -5              | 6                    | 21                            |
| Sep   | 31               | 23                    | 9                     | -3              | 27                   | 62                            |
| Oct   | 32               | 24                    | 11                    | 0               | 72                   | 110                           |
| Nov   | 33               | 24                    | 13                    | 2               | 117                  | 65                            |
| Dec   | 32               | 25                    | 14                    | 4               | 105                  | 102                           |
| Year  | 35               | 22                    | 10                    | -8              | 713                  | 188                           |

Table 33: Environmental Data for Durban, South Africa (South African Weather Service, n.d.)

| Month | Temperature (°C) |                       |                       |                 | Precipitation        |                               |
|-------|------------------|-----------------------|-----------------------|-----------------|----------------------|-------------------------------|
|       | Highest Recorded | Average Daily Maximum | Average Daily Minimum | Lowest Recorded | Average Monthly (mm) | Highest 24 Hour Rainfall (mm) |
| Jan   | 36               | 28                    | 21                    | 14              | 134                  | 110                           |
| Feb   | 34               | 28                    | 21                    | 13              | 113                  | 197                           |
| March | 35               | 28                    | 20                    | 12              | 120                  | 160                           |
| April | 36               | 26                    | 17                    | 9               | 73                   | 106                           |
| May   | 34               | 25                    | 14                    | 5               | 59                   | 111                           |
| June  | 36               | 23                    | 11                    | 4               | 28                   | 109                           |
| July  | 34               | 23                    | 11                    | 3               | 39                   | 69                            |
| Aug   | 36               | 23                    | 13                    | 3               | 62                   | 91                            |
| Sep   | 37               | 23                    | 15                    | 5               | 73                   | 132                           |
| Oct   | 40               | 24                    | 17                    | 8               | 98                   | 105                           |
| Nov   | 34               | 25                    | 18                    | 10              | 108                  | 94                            |
| Dec   | 36               | 27                    | 20                    | 12              | 102                  | 163                           |
| Year  | 40               | 25                    | 17                    | 3               | 1009                 | 197                           |

Table 34: Environmental Data for Kimberley, South Africa (South African Weather Service, n.d.)

| Month | Temperature (°C) |                       |                       |                 | Precipitation        |                               |
|-------|------------------|-----------------------|-----------------------|-----------------|----------------------|-------------------------------|
|       | Highest Recorded | Average Daily Maximum | Average Daily Minimum | Lowest Recorded | Average Monthly (mm) | Highest 24 Hour Rainfall (mm) |
| Jan   | 40               | 33                    | 18                    | 7               | 57                   | 45                            |
| Feb   | 40               | 31                    | 17                    | 6               | 76                   | 88                            |
| March | 36               | 29                    | 15                    | 2               | 65                   | 54                            |
| April | 35               | 25                    | 11                    | 0               | 49                   | 51                            |
| May   | 31               | 21                    | 7                     | -6              | 16                   | 55                            |
| June  | 27               | 18                    | 3                     | -7              | 7                    | 18                            |
| July  | 27               | 19                    | 3                     | -8              | 7                    | 22                            |
| Aug   | 31               | 21                    | 5                     | -7              | 7                    | 26                            |
| Sep   | 36               | 26                    | 9                     | -6              | 12                   | 44                            |
| Oct   | 38               | 28                    | 12                    | -1              | 30                   | 35                            |
| Nov   | 39               | 30                    | 15                    | 3               | 42                   | 60                            |
| Dec   | 40               | 32                    | 17                    | 5               | 46                   | 60                            |
| Year  | 40               | 26                    | 11                    | -8              | 414                  | 88                            |

## Appendix B - Curing Conditions

### Controlled Conditions

Table 35: Controlled Curing Conditions for curing environments and techniques

| Curing Technique | Location                      | Humidity (%)                             | Temperature (°C) |
|------------------|-------------------------------|--|------------------|
| "Summer"         | Chemical and Creep Laboratory | $45 \pm 5$                               | $22 \pm 2$       |
| Water            | Curing Tanks                  | 100                                      | $23 \pm 2$       |
| Hessian          | Chemical and Creep Laboratory | 100 (0-7 days)<br>$45 \pm 5$ (7-28 days) | $22 \pm 2$       |

### Winter Conditions (Outside)

Environmental conditions experienced for the duration of the exposure period was recorded and are shown in Figure 74 and Figure 75 below.

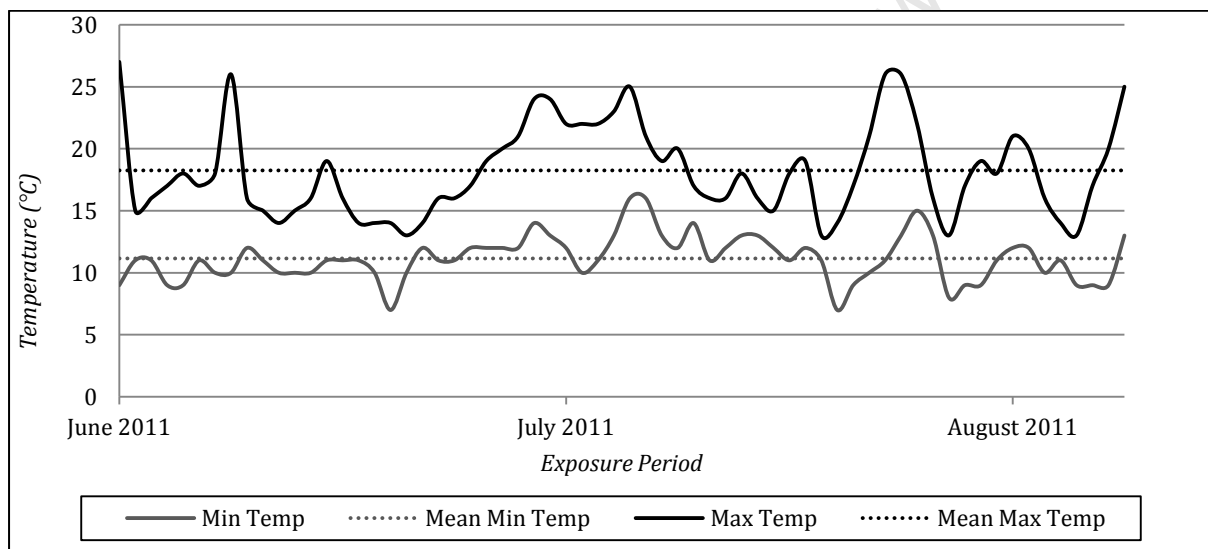


Figure 74: Environmental Conditions - Max and Min Temperature (14 June - 16 August 2011)

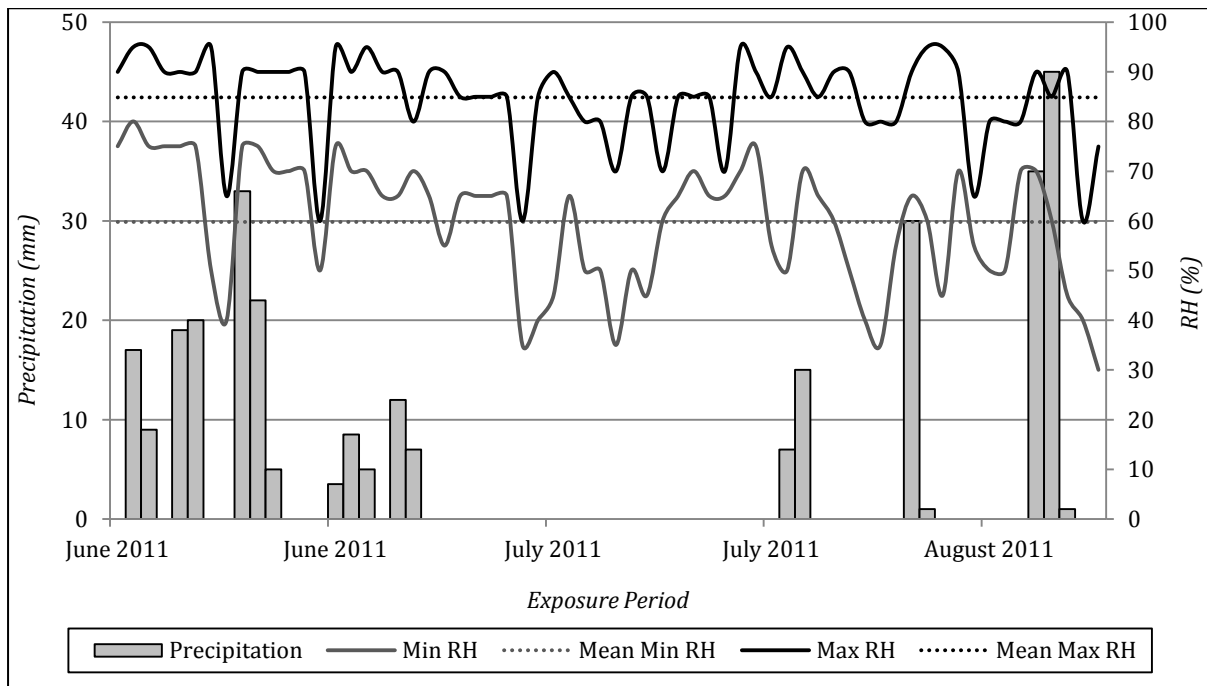


Figure 75: Environmental Conditions - Max and Min RH and Precipitation (14 June-16 August 2011)

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## Appendix C - Compressive Strength Results

| Mix  | Sample | Dimensions |        |        | Mass (kg) | Density (kg/m <sup>3</sup> ) | Ave. Density (kg/m <sup>3</sup> ) | Load (kN) | 28 day strength (MPa) | Ave. 28 day strength (MPa) | Std Dev (MPa) |
|------|--------|------------|--------|--------|-----------|------------------------------|-----------------------------------|-----------|-----------------------|----------------------------|---------------|
|      |        | l (mm)     | b (mm) | h (mm) |           |                              |                                   |           |                       |                            |               |
| 4C11 | i      | 100        | 100    | 100    | 2.390     | 2390                         | 2385                              | 444       | 44.4                  | 45.6                       | 1.3           |
|      | ii     |            |        |        | 2.390     | 2390                         |                                   | 453       | 45.3                  |                            |               |
|      | iii    |            |        |        | 2.375     | 2375                         |                                   | 470       | 47                    |                            |               |
| 4C10 | i      |            |        |        | 2.360     | 2360                         | 2382                              | 501       | 50.1                  | 52.6                       | 3.5           |
|      | ii     |            |        |        | 2.365     | 2365                         |                                   | 512       | 51.2                  |                            |               |
|      | iii    |            |        |        | 2.420     | 2420                         |                                   | 566       | 56.6                  |                            |               |
| 4C21 | i      |            |        |        | 2.410     | 2410                         | 2408                              | 392       | 39.2                  | 39.8                       | 1.4           |
|      | ii     |            |        |        | 2.390     | 2390                         |                                   | 388       | 38.8                  |                            |               |
|      | iii    |            |        |        | 2.425     | 2425                         |                                   | 414       | 41.4                  |                            |               |
| 4C20 | i      |            |        |        | 2.395     | 2395                         | 2405                              | 468       | 46.8                  | 47.1                       | 0.5           |
|      | ii     |            |        |        | 2.420     | 2420                         |                                   | 476       | 47.6                  |                            |               |
|      | iii    |            |        |        | 2.400     | 2400                         |                                   | 468       | 46.8                  |                            |               |
| 4CW  | i      |            |        |        | 2.395     | 2395                         | 2415                              | 570       | 57                    | 56.7                       | 1.4           |
|      | ii     |            |        |        | 2.405     | 2405                         |                                   | 579       | 57.9                  |                            |               |
|      | iii    |            |        |        | 2.445     | 2445                         |                                   | 551       | 55.1                  |                            |               |
| 4CI  | i      | 2.380      | 2380   | 2400   | 457       | 45.7                         | 44.8                              | 0.8       |                       |                            |               |
|      | ii     | 2.390      | 2390   |        | 441       | 44.1                         |                                   |           |                       |                            |               |
|      | iii    | 2.430      | 2430   |        | 447       | 44.7                         |                                   |           |                       |                            |               |
| 4CO  | i      | 2.405      | 2405   | 2408   | 530       | 53                           | 53.4                              | 1.3       |                       |                            |               |
|      | ii     | 2.410      | 2410   |        | 523       | 52.3                         |                                   |           |                       |                            |               |
|      | iii    | 2.410      | 2410   |        | 548       | 54.8                         |                                   |           |                       |                            |               |
| 4CH  | i      | 2.380      | 2380   | 2382   | 580       | 58                           | 57.1                              | 1.8       |                       |                            |               |
|      | ii     | 2.375      | 2375   |        | 550       | 55                           |                                   |           |                       |                            |               |
|      | iii    | 2.390      | 2390   |        | 582       | 58.2                         |                                   |           |                       |                            |               |
| 4CC  | i      | 2.395      | 2395   | 2390   | 510       | 51                           | 51.5                              | 0.6       |                       |                            |               |
|      | ii     | 2.395      | 2395   |        | 522       | 52.2                         |                                   |           |                       |                            |               |
|      | iii    | 2.380      | 2380   |        | 512       | 51.2                         |                                   |           |                       |                            |               |

| Mix  | Sample | Dimensions |        |        | Mass (kg) | Density (kg/m <sup>3</sup> ) | Ave. Density (kg/m <sup>3</sup> ) | Load (kN) | 28 day strength (MPa) | Ave. 28 day strength (MPa) | Std Dev (MPa) |
|------|--------|------------|--------|--------|-----------|------------------------------|-----------------------------------|-----------|-----------------------|----------------------------|---------------|
|      |        | l (mm)     | b (mm) | h (mm) |           |                              |                                   |           |                       |                            |               |
| 4F1I | i      | 100        | 100    | 100    | 2.415     | 2415                         | 2423                              | 384       | 38.4                  | 39.5                       | 1.2           |
|      | ii     |            |        |        | 2.435     | 2435                         |                                   | 408       | 40.8                  |                            |               |
|      | iii    |            |        |        | 2.420     | 2420                         |                                   | 392       | 39.2                  |                            |               |
| 4F1O | i      |            |        |        | 2.405     | 2405                         | 2400                              | 400       | 40                    | 40.6                       | 1.0           |
|      | ii     |            |        |        | 2.415     | 2415                         |                                   | 400       | 40                    |                            |               |
|      | iii    |            |        |        | 2.380     | 2380                         |                                   | 418       | 41.8                  |                            |               |
| 4F2I | i      |            |        |        | 2.370     | 2370                         | 2388                              | 361       | 36.1                  | 33.9                       | 2.0           |
|      | ii     |            |        |        | 2.375     | 2375                         |                                   | 334       | 33.4                  |                            |               |
|      | iii    |            |        |        | 2.420     | 2420                         |                                   | 322       | 32.2                  |                            |               |
| 4F2O | i      |            |        |        | 2.400     | 2400                         | 2403                              | 292       | 29.2                  | 32.0                       | 2.6           |
|      | ii     |            |        |        | 2.395     | 2395                         |                                   | 342       | 34.2                  |                            |               |
|      | iii    |            |        |        | 2.415     | 2415                         |                                   | 326       | 32.6                  |                            |               |
| 4FW  | i      |            |        |        | 2.445     | 2445                         | 2427                              | 624       | 62.4                  | 60.8                       | 1.7           |
|      | ii     |            |        |        | 2.415     | 2415                         |                                   | 590       | 59                    |                            |               |
|      | iii    |            |        |        | 2.420     | 2420                         |                                   | 609       | 60.9                  |                            |               |
| 4FI  | i      | 2.430      | 2430   | 2403   | 348       | 34.8                         | 33.3                              | 1.7       |                       |                            |               |
|      | ii     | 2.375      | 2375   |        | 338       | 33.8                         |                                   |           |                       |                            |               |
|      | iii    | 2.405      | 2405   |        | 314       | 31.4                         |                                   |           |                       |                            |               |
| 4FO  | i      | 2.375      | 2375   | 2388   | 419       | 41.9                         | 44.9                              | 3.1       |                       |                            |               |
|      | ii     | 2.380      | 2380   |        | 447       | 44.7                         |                                   |           |                       |                            |               |
|      | iii    | 2.410      | 2410   |        | 480       | 48                           |                                   |           |                       |                            |               |
| 4FH  | i      | 2.415      | 2415   | 2407   | 531       | 53.1                         | 53.5                              | 0.4       |                       |                            |               |
|      | ii     | 2.425      | 2425   |        | 536       | 53.6                         |                                   |           |                       |                            |               |
|      | iii    | 2.380      | 2380   |        | 538       | 53.8                         |                                   |           |                       |                            |               |
| 4FC  | i      | 2.395      | 2395   | 2410   | 456       | 45.6                         | 44.9                              | 0.6       |                       |                            |               |
|      | ii     | 2.390      | 2390   |        | 448       | 44.8                         |                                   |           |                       |                            |               |
|      | iii    | 2.445      | 2445   |        | 444       | 44.4                         |                                   |           |                       |                            |               |

| Mix  | Sample | Dimensions |        |        | Mass (kg) | Density (kg/m <sup>3</sup> ) | Ave. Density (kg/m <sup>3</sup> ) | Load (kN) | 28 day strength (MPa) | Ave. 28 day strength (MPa) | Std Dev (MPa) |
|------|--------|------------|--------|--------|-----------|------------------------------|-----------------------------------|-----------|-----------------------|----------------------------|---------------|
|      |        | l (mm)     | b (mm) | h (mm) |           |                              |                                   |           |                       |                            |               |
| 4G1I | i      | 100        | 100    | 100    | 2.405     | 2405                         | 2408                              | 328       | 32.8                  | 32.6                       | 0.2           |
|      | ii     |            |        |        | 2.415     | 2415                         |                                   | 326       | 32.6                  |                            |               |
|      | iii    |            |        |        | 2.405     | 2405                         |                                   | 325       | 32.5                  |                            |               |
| 4G10 | i      |            |        |        | 2.425     | 2425                         | 2413                              | 368       | 36.8                  | 36.8                       | 0.2           |
|      | ii     |            |        |        | 2.425     | 2425                         |                                   | 366       | 36.6                  |                            |               |
|      | iii    |            |        |        | 2.390     | 2390                         |                                   | 370       | 37                    |                            |               |
| 4G2I | i      |            |        |        | 2.425     | 2425                         | 2420                              | 306       | 30.6                  | 27.6                       | 2.6           |
|      | ii     |            |        |        | 2.425     | 2425                         |                                   | 266       | 26.6                  |                            |               |
|      | iii    |            |        |        | 2.410     | 2410                         |                                   | 256       | 25.6                  |                            |               |
| 4G20 | i      |            |        |        | 2.420     | 2420                         | 2407                              | 321       | 32.1                  | 33.1                       | 1.3           |
|      | ii     |            |        |        | 2.420     | 2420                         |                                   | 345       | 34.5                  |                            |               |
|      | iii    |            |        |        | 2.380     | 2380                         |                                   | 326       | 32.6                  |                            |               |
| 4GW  | i      | 2.390      | 2390   | 2395   | 499       | 49.9                         | 51.4                              | 1.3       |                       |                            |               |
|      | ii     | 2.395      | 2395   |        | 525       | 52.5                         |                                   |           |                       |                            |               |
|      | iii    | 2.400      | 2400   |        | 518       | 51.8                         |                                   |           |                       |                            |               |
| 4GI  | i      | 2.395      | 2395   | 2410   | 247       | 24.7                         | 26.6                              | 1.6       |                       |                            |               |
|      | ii     | 2.415      | 2415   |        | 276       | 27.6                         |                                   |           |                       |                            |               |
|      | iii    | 2.420      | 2420   |        | 274       | 27.4                         |                                   |           |                       |                            |               |
| 4GO  | i      | 2.430      | 2430   | 2425   | 340       | 34                           | 35.4                              | 2.0       |                       |                            |               |
|      | ii     | 2.425      | 2425   |        | 377       | 37.7                         |                                   |           |                       |                            |               |
|      | iii    | 2.420      | 2420   |        | 346       | 34.6                         |                                   |           |                       |                            |               |
| 4GH  | i      | 2.435      | 2435   | 2423   | 449       | 44.9                         | 47.0                              | 2.8       |                       |                            |               |
|      | ii     | 2.415      | 2415   |        | 502       | 50.2                         |                                   |           |                       |                            |               |
|      | iii    | 2.420      | 2420   |        | 459       | 45.9                         |                                   |           |                       |                            |               |
| 4GC  | i      | 2.450      | 2450   | 2433   | 450       | 45                           | 45.1                              | 0.4       |                       |                            |               |
|      | ii     | 2.425      | 2425   |        | 448       | 44.8                         |                                   |           |                       |                            |               |
|      | iii    | 2.425      | 2425   |        | 456       | 45.6                         |                                   |           |                       |                            |               |

| Mix  | Sample | Dimensions |        |        | Mass (kg) | Density (kg/m <sup>3</sup> ) | Ave. Density (kg/m <sup>3</sup> ) | Load (kN) | 28 day strength (MPa) | Ave. 28 day strength (MPa) | Std Dev (MPa) |
|------|--------|------------|--------|--------|-----------|------------------------------|-----------------------------------|-----------|-----------------------|----------------------------|---------------|
|      |        | l (mm)     | b (mm) | h (mm) |           |                              |                                   |           |                       |                            |               |
| 4S11 | i      | 100        | 100    | 100    | 2.360     | 2360                         | 2345                              | 448       | 44.8                  | 45.4                       | 1.0           |
|      | ii     |            |        |        | 2.315     | 2315                         |                                   | 448       | 44.8                  |                            |               |
|      | iii    |            |        |        | 2.360     | 2360                         |                                   | 466       | 46.6                  |                            |               |
| 4S10 | i      |            |        |        | 2.355     | 2355                         | 2317                              | 413       | 41.3                  | 45.1                       | 3.3           |
|      | ii     |            |        |        | 2.310     | 2310                         |                                   | 476       | 47.6                  |                            |               |
|      | iii    |            |        |        | 2.285     | 2285                         |                                   | 464       | 46.4                  |                            |               |
| 4S21 | i      |            |        |        | 2.275     | 2275                         | 2290                              | 438       | 43.8                  | 44.3                       | 1.2           |
|      | ii     |            |        |        | 2.310     | 2310                         |                                   | 434       | 43.4                  |                            |               |
|      | iii    |            |        |        | 2.285     | 2285                         |                                   | 456       | 45.6                  |                            |               |
| 4S20 | i      |            |        |        | 2.320     | 2320                         | 2317                              | 420       | 42                    | 41.6                       | 1.1           |
|      | ii     |            |        |        | 2.300     | 2300                         |                                   | 404       | 40.4                  |                            |               |
|      | iii    |            |        |        | 2.330     | 2330                         |                                   | 424       | 42.4                  |                            |               |
| 4SW  | i      |            |        |        | 2.360     | 2360                         | 2370                              | 565       | 56.5                  | 58.6                       | 2.2           |
|      | ii     |            |        |        | 2.385     | 2385                         |                                   | 586       | 58.6                  |                            |               |
|      | iii    |            |        |        | 2.365     | 2365                         |                                   | 608       | 60.8                  |                            |               |
| 4SI  | i      | 2.355      | 2355   | 2355   | 412       | 41.2                         | 42.5                              | 1.8       |                       |                            |               |
|      | ii     | 2.330      | 2330   |        | 445       | 44.5                         |                                   |           |                       |                            |               |
|      | iii    | 2.380      | 2380   |        | 418       | 41.8                         |                                   |           |                       |                            |               |
| 4SO  | i      | 2.290      | 2290   | 2280   | 416       | 41.6                         | 40.5                              | 1.7       |                       |                            |               |
|      | ii     | 2.255      | 2255   |        | 414       | 41.4                         |                                   |           |                       |                            |               |
|      | iii    | 2.295      | 2295   |        | 386       | 38.6                         |                                   |           |                       |                            |               |
| 4SH  | i      | 2.310      | 2310   | 2280   | 484       | 48.4                         | 45.3                              | 2.7       |                       |                            |               |
|      | ii     | 2.255      | 2255   |        | 434       | 43.4                         |                                   |           |                       |                            |               |
|      | iii    | 2.275      | 2275   |        | 440       | 44                           |                                   |           |                       |                            |               |
| 4SC  | i      | 2.280      | 2280   | 2285   | 451       | 45.1                         | 45.8                              | 1.7       |                       |                            |               |
|      | ii     | 2.300      | 2300   |        | 477       | 47.7                         |                                   |           |                       |                            |               |
|      | iii    | 2.275      | 2275   |        | 446       | 44.6                         |                                   |           |                       |                            |               |

| Mix  | Sample | Dimensions |        |        | Mass (kg) | Density (kg/m <sup>3</sup> ) | Ave. Density (kg/m <sup>3</sup> ) | Load (kN) | 28 day strength (MPa) | Ave. 28 day strength (MPa) | Std Dev (MPa) |     |
|------|--------|------------|--------|--------|-----------|------------------------------|-----------------------------------|-----------|-----------------------|----------------------------|---------------|-----|
|      |        | l (mm)     | b (mm) | h (mm) |           |                              |                                   |           |                       |                            |               |     |
| 5C1I | i      | 100        | 100    | 100    | 2.415     | 2415                         | 2437                              | 362       | 36.2                  | 34.5                       | 1.5           |     |
|      | ii     |            |        |        | 2.450     | 2450                         |                                   | 340       | 34                    |                            |               |     |
|      | iii    |            |        |        | 2.445     | 2445                         |                                   | 333       | 33.3                  |                            |               |     |
| 5C1O | i      |            |        |        | 2.435     | 2435                         | 2435                              | 368       | 36.8                  | 35.9                       | 35.9          | 0.9 |
|      | ii     |            |        |        | 2.435     | 2435                         |                                   | 359       | 35.9                  |                            |               |     |
|      | iii    |            |        |        | 2.435     | 2435                         |                                   | 351       | 35.1                  |                            |               |     |
| 5C2I | i      |            |        |        | 2.415     | 2415                         | 2403                              | 302       | 30.2                  | 30.4                       | 30.7          | 0.6 |
|      | ii     |            |        |        | 2.385     | 2385                         |                                   | 304       | 30.4                  |                            |               |     |
|      | iii    |            |        |        | 2.410     | 2410                         |                                   | 314       | 31.4                  |                            |               |     |
| 5C2O | i      |            |        |        | 2.430     | 2430                         | 2410                              | 297       | 29.7                  | 28.2                       | 30.1          | 2.2 |
|      | ii     |            |        |        | 2.400     | 2400                         |                                   | 282       | 28.2                  |                            |               |     |
|      | iii    |            |        |        | 2.400     | 2400                         |                                   | 325       | 32.5                  |                            |               |     |
| 5CW  | i      |            |        |        | 2.450     | 2450                         | 2448                              | 464       | 46.4                  | 47.3                       | 47.1          | 0.6 |
|      | ii     |            |        |        | 2.445     | 2445                         |                                   | 473       | 47.3                  |                            |               |     |
|      | iii    |            |        |        | 2.450     | 2450                         |                                   | 476       | 47.6                  |                            |               |     |
| 5CI  | i      |            |        |        | 2.405     | 2405                         | 2412                              | 316       | 31.6                  | 31                         | 31.7          | 0.8 |
|      | ii     |            |        |        | 2.420     | 2420                         |                                   | 310       | 31                    |                            |               |     |
|      | iii    |            |        |        | 2.410     | 2410                         |                                   | 326       | 32.6                  |                            |               |     |
| 5CO  | i      | 2.455      | 2455   | 2448   | 314       | 31.4                         | 34                                | 32.5      | 1.3                   |                            |               |     |
|      | ii     | 2.440      | 2440   |        | 340       | 34                           |                                   |           |                       |                            |               |     |
|      | iii    | 2.450      | 2450   |        | 321       | 32.1                         |                                   |           |                       |                            |               |     |
| 5CH  | i      | 2.450      | 2450   | 2433   | 433       | 43.3                         | 43.7                              | 44.3      | 1.4                   |                            |               |     |
|      | ii     | 2.435      | 2435   |        | 437       | 43.7                         |                                   |           |                       |                            |               |     |
|      | iii    | 2.415      | 2415   |        | 459       | 45.9                         |                                   |           |                       |                            |               |     |
| 5CC  | i      | 2.440      | 2440   | 2452   | 422       | 42.2                         | 38.7                              | 41.0      | 2.0                   |                            |               |     |
|      | ii     | 2.440      | 2440   |        | 387       | 38.7                         |                                   |           |                       |                            |               |     |
|      | iii    | 2.475      | 2475   |        | 421       | 42.1                         |                                   |           |                       |                            |               |     |

| Mix  | Sample | Dimensions |        |        | Mass (kg) | Density (kg/m <sup>3</sup> ) | Ave. Density (kg/m <sup>3</sup> ) | Load (kN) | 28 day strength (MPa) | Ave. 28 day strength (MPa) | Std Dev (MPa) |
|------|--------|------------|--------|--------|-----------|------------------------------|-----------------------------------|-----------|-----------------------|----------------------------|---------------|
|      |        | l (mm)     | b (mm) | h (mm) |           |                              |                                   |           |                       |                            |               |
| 6C11 | i      | 100        | 100    | 100    | 2.390     | 2390                         | 2412                              | 251       | 25.1                  | 25.3                       | 0.6           |
|      | ii     |            |        |        | 2.410     | 2410                         |                                   | 249       | 24.9                  |                            |               |
|      | iii    |            |        |        | 2.435     | 2435                         |                                   | 260       | 26                    |                            |               |
| 6C10 | i      |            |        |        | 2.400     | 2400                         | 2423                              | 280       | 28                    | 27.7                       | 0.7           |
|      | ii     |            |        |        | 2.460     | 2460                         |                                   | 269       | 26.9                  |                            |               |
|      | iii    |            |        |        | 2.410     | 2410                         |                                   | 282       | 28.2                  |                            |               |
| 6C21 | i      |            |        |        | 2.420     | 2420                         | 2398                              | 214       | 21.4                  | 21.6                       | 0.3           |
|      | ii     |            |        |        | 2.380     | 2380                         |                                   | 219       | 21.9                  |                            |               |
|      | iii    |            |        |        | 2.395     | 2395                         |                                   | 214       | 21.4                  |                            |               |
| 6C20 | i      |            |        |        | 2.430     | 2430                         | 2413                              | 257       | 25.7                  | 25.1                       | 0.6           |
|      | ii     |            |        |        | 2.420     | 2420                         |                                   | 246       | 24.6                  |                            |               |
|      | iii    |            |        |        | 2.390     | 2390                         |                                   | 250       | 25                    |                            |               |
| 6CW  | i      |            |        |        | 2.445     | 2445                         | 2432                              | 323       | 32.3                  | 31.4                       | 1.4           |
|      | ii     |            |        |        | 2.420     | 2420                         |                                   | 320       | 32                    |                            |               |
|      | iii    |            |        |        | 2.430     | 2430                         |                                   | 298       | 29.8                  |                            |               |
| 6CI  | i      | 2.410      | 2410   | 2417   | 211       | 21.1                         | 21.2                              | 0.8       |                       |                            |               |
|      | ii     | 2.405      | 2405   |        | 205       | 20.5                         |                                   |           |                       |                            |               |
|      | iii    | 2.435      | 2435   |        | 220       | 22                           |                                   |           |                       |                            |               |
| 6CO  | i      | 2.415      | 2415   | 2420   | 238       | 23.8                         | 23.7                              | 0.2       |                       |                            |               |
|      | ii     | 2.425      | 2425   |        | 237       | 23.7                         |                                   |           |                       |                            |               |
|      | iii    | 2.420      | 2420   |        | 235       | 23.5                         |                                   |           |                       |                            |               |
| 6CH  | i      | 2.400      | 2400   | 2413   | 289       | 28.9                         | 28.5                              | 0.4       |                       |                            |               |
|      | ii     | 2.425      | 2425   |        | 284       | 28.4                         |                                   |           |                       |                            |               |
|      | iii    | 2.415      | 2415   |        | 281       | 28.1                         |                                   |           |                       |                            |               |
| 6CC  | i      | 2.425      | 2425   | 2415   | 262       | 26.2                         | 27.5                              | 1.5       |                       |                            |               |
|      | ii     | 2.385      | 2385   |        | 291       | 29.1                         |                                   |           |                       |                            |               |
|      | iii    | 2.435      | 2435   |        | 273       | 27.3                         |                                   |           |                       |                            |               |

| Mix  | Sample | Dimensions |     |       | Mass (kg) | Density (kg/m <sup>3</sup> ) | Ave. Density (kg/m <sup>3</sup> ) | Load (kN) | 28 day strength (MPa) | Ave. 28 day strength (MPa) | Std Dev (MPa) |
|------|--------|------------|-----|-------|-----------|------------------------------|-----------------------------------|-----------|-----------------------|----------------------------|---------------|
|      |        | l          | b   | h     |           |                              |                                   |           |                       |                            |               |
| 4CWP | i      | 100        | 100 | 100.0 | 2.435     | 2435                         | 2438                              | 596       | 59.6                  | 60.7                       | 1.2           |
|      | ii     |            |     |       | 2.435     | 2435                         |                                   | 620       | 62                    |                            |               |
|      | iii    |            |     |       | 2.445     | 2445                         |                                   | 604       | 60.4                  |                            |               |
| 4CIP | i      | 100        | 100 | 100.0 | 2.405     | 2405                         | 2412                              | 464       | 46.4                  | 46.7                       | 0.6           |
|      | ii     |            |     |       | 2.405     | 2405                         |                                   | 463       | 46.3                  |                            |               |
|      | iii    |            |     |       | 2.425     | 2425                         |                                   | 473       | 47.3                  |                            |               |
| 4FWP | i      | 100        | 100 | 100.0 | 2.405     | 2405                         | 2423                              | 532       | 53.2                  | 53.9                       | 0.8           |
|      | ii     |            |     |       | 2.415     | 2415                         |                                   | 548       | 54.8                  |                            |               |
|      | iii    |            |     |       | 2.450     | 2450                         |                                   | 538       | 53.8                  |                            |               |
| 4FIP | i      | 100        | 100 | 100.0 | 2.435     | 2435                         | 2440                              | 365       | 36.5                  | 37.5                       | 1.7           |
|      | ii     |            |     |       | 2.450     | 2450                         |                                   | 366       | 36.6                  |                            |               |
|      | iii    |            |     |       | 2.435     | 2435                         |                                   | 395       | 39.5                  |                            |               |
| 4GWP | i      | 100        | 100 | 100   | 2.420     | 2420                         | 2438                              | 614       | 61.4                  | 59.2                       | 1.9           |
|      | ii     |            |     |       | 2.465     | 2465                         |                                   | 584       | 58.4                  |                            |               |
|      | iii    |            |     |       | 2.430     | 2430                         |                                   | 578       | 57.8                  |                            |               |
| 4GIP | i      | 100        | 100 | 100   | 2.440     | 2440                         | 2438                              | 294       | 29.4                  | 30.2                       | 0.9           |
|      | ii     |            |     |       | 2.435     | 2435                         |                                   | 311       | 31.1                  |                            |               |
|      | iii    |            |     |       | 2.440     | 2440                         |                                   | 301       | 30.1                  |                            |               |
| 4SWP | i      | 100        | 100 | 100   | 2.315     | 2315                         | 2338                              | 504       | 50.4                  | 49.2                       | 1.3           |
|      | ii     |            |     |       | 2.360     | 2360                         |                                   | 478       | 47.8                  |                            |               |
|      | iii    |            |     |       | 2.340     | 2340                         |                                   | 493       | 49.3                  |                            |               |
| 4SIP | i      | 100        | 100 | 100   | 2.325     | 2325                         | 2342                              | 412       | 41.2                  | 40.9                       | 0.8           |
|      | ii     |            |     |       | 2.360     | 2360                         |                                   | 414       | 41.4                  |                            |               |
|      | iii    |            |     |       | 2.340     | 2340                         |                                   | 400       | 40                    |                            |               |
| 5CWP | i      | 100        | 100 | 100   | 2.405     | 2405                         | 2415                              | 430       | 43                    | 42.9                       | 0.1           |
|      | ii     |            |     |       | 2.410     | 2410                         |                                   | 430       | 43                    |                            |               |
|      | iii    |            |     |       | 2.430     | 2430                         |                                   | 428       | 42.8                  |                            |               |
| 5CIP | i      | 100        | 100 | 100   | 2.400     | 2400                         | 2393                              | 324       | 32.4                  | 32.3                       | 0.1           |
|      | ii     |            |     |       | 2.395     | 2395                         |                                   | 324       | 32.4                  |                            |               |
|      | iii    |            |     |       | 2.385     | 2385                         |                                   | 322       | 32.2                  |                            |               |

| Mix  | Sample | Dimensions |        |        | Mass (kg) | Density (kg/m <sup>3</sup> ) | Ave. Density (kg/m <sup>3</sup> ) | Load (kN) | 28 day strength (MPa) | Ave. 28 day strength (MPa) | Std Dev (MPa) |
|------|--------|------------|--------|--------|-----------|------------------------------|-----------------------------------|-----------|-----------------------|----------------------------|---------------|
|      |        | l (mm)     | b (mm) | h (mm) |           |                              |                                   |           |                       |                            |               |
| 4CWX | i      | 100        | 100    | 100.0  | 2.455     | 2455                         | 2435                              | 610       | 61                    | 62.4                       | 1.8           |
|      | ii     |            |        |        | 2.415     | 2415                         |                                   | 618       | 61.8                  |                            |               |
|      | iii    |            |        |        | 2.435     | 2435                         |                                   | 644       | 64.4                  |                            |               |
| 4CIX | i      | 100        | 100    | 100.0  | 2.415     | 2415                         | 2408                              | 462       | 46.2                  | 45.2                       | 0.9           |
|      | ii     |            |        |        | 2.395     | 2395                         |                                   | 450       | 45                    |                            |               |
|      | iii    |            |        |        | 2.415     | 2415                         |                                   | 445       | 44.5                  |                            |               |
| 4FWX | i      | 100        | 100    | 100.0  | 2.420     | 2420                         | 2428                              | 563       | 56.3                  | 57.5                       | 1.8           |
|      | ii     |            |        |        | 2.405     | 2405                         |                                   | 596       | 59.6                  |                            |               |
|      | iii    |            |        |        | 2.460     | 2460                         |                                   | 566       | 56.6                  |                            |               |
| 4FIX | i      | 100        | 100    | 100.0  | 2.400     | 2400                         | 2430                              | 396       | 39.6                  | 39.5                       | 2.7           |
|      | ii     |            |        |        | 2.440     | 2440                         |                                   | 368       | 36.8                  |                            |               |
|      | iii    |            |        |        | 2.450     | 2450                         |                                   | 422       | 42.2                  |                            |               |
| 4GWX | i      | 100        | 100    | 100.0  | 2.465     | 2465                         | 2465                              | 563       | 56.3                  | 58.6                       | 2.5           |
|      | ii     |            |        |        | 2.460     | 2460                         |                                   | 613       | 61.3                  |                            |               |
|      | iii    |            |        |        | 2.470     | 2470                         |                                   | 582       | 58.2                  |                            |               |
| 4GIX | i      | 100        | 100    | 100.0  | 2.440     | 2440                         | 2427                              | 370       | 37                    | 36.3                       | 1.2           |
|      | ii     |            |        |        | 2.435     | 2435                         |                                   | 350       | 35                    |                            |               |
|      | iii    |            |        |        | 2.405     | 2405                         |                                   | 370       | 37                    |                            |               |
| 4SWX | i      | 100        | 100    | 100.0  | 2.360     | 2360                         | 2362                              | 644       | 64.4                  | 65.7                       | 1.7           |
|      | ii     |            |        |        | 2.355     | 2355                         |                                   | 676       | 67.6                  |                            |               |
|      | iii    |            |        |        | 2.370     | 2370                         |                                   | 650       | 65                    |                            |               |
| 4SIX | i      | 100        | 100    | 100.0  | 2.360     | 2360                         | 2343                              | 550       | 55                    | 54.2                       | 1.0           |
|      | ii     |            |        |        | 2.365     | 2365                         |                                   | 545       | 54.5                  |                            |               |
|      | iii    |            |        |        | 2.305     | 2305                         |                                   | 530       | 53                    |                            |               |
| 5CWX | i      | 100        | 100    | 100.0  | 2.360     | 2360                         | 2367                              | 496       | 49.6                  | 48.0                       | 1.4           |
|      | ii     |            |        |        | 2.365     | 2365                         |                                   | 473       | 47.3                  |                            |               |
|      | iii    |            |        |        | 2.375     | 2375                         |                                   | 470       | 47                    |                            |               |
| 5CIX | i      | 100        | 100    | 100.0  | 2.355     | 2355                         | 2358                              | 384       | 38.4                  | 38.8                       | 0.8           |
|      | ii     |            |        |        | 2.365     | 2365                         |                                   | 397       | 39.7                  |                            |               |
|      | iii    |            |        |        | 2.355     | 2355                         |                                   | 382       | 38.2                  |                            |               |

## Appendix D - OPI Results

| Sample | Sample no. | k (m/s)  |         |         | OPI        |       |         |      |
|--------|------------|----------|---------|---------|------------|-------|---------|------|
|        |            | Measured | Mean    | Std Dev | Calculated | Mean  | Std Dev |      |
| 4C     | 4CW        | i        | 2.7E-11 | 3.1E-11 | 5.7E-12    | 10.56 | 10.50   | 0.08 |
|        |            | ii       | 3.5E-11 |         |            | 10.45 |         |      |
|        |            | iii      | 2.6E-11 |         |            | 10.59 |         |      |
|        |            | iv       | 3.7E-11 |         |            | 10.43 |         |      |
|        | 4CH        | i        | 4.9E-11 | 3.8E-11 | 1.2E-11    | 10.31 | 10.42   | 0.14 |
|        |            | ii       | 4.8E-11 |         |            | 10.32 |         |      |
|        |            | iii      | 2.7E-11 |         |            | 10.56 |         |      |
|        |            | iv       | 2.8E-11 |         |            | 10.55 |         |      |
|        | 4CO        | i        | 3.4E-11 | 4.5E-11 | 9.1E-12    | 10.46 | 10.35   | 0.09 |
|        |            | ii       | 5.2E-11 |         |            | 10.28 |         |      |
|        |            | iii      | 5.3E-11 |         |            | 10.28 |         |      |
|        |            | iv       | 4.1E-11 |         |            | 10.39 |         |      |
|        | 4C10       | i        | 7.8E-11 | 6.8E-11 | 7.4E-12    | 10.11 | 10.17   | 0.05 |
|        |            | ii       | 6.5E-11 |         |            | 10.19 |         |      |
|        |            | iii      | 6.3E-11 |         |            | 10.20 |         |      |
|        |            | iv       | 6.4E-11 |         |            | 10.20 |         |      |
|        | 4C20       | i        | 8.0E-11 | 8.0E-11 | 4.4E-12    | 10.10 | 10.09   | 0.02 |
|        |            | ii       | 8.5E-11 |         |            | 10.07 |         |      |
|        |            | iii      | 1.6E-10 |         |            | 9.80  |         |      |
|        |            | iv       | 7.7E-11 |         |            | 10.12 |         |      |
|        | 4CC        | i        | 4.8E-11 | 5.9E-11 | 1.2E-11    | 10.32 | 10.23   | 0.09 |
|        |            | ii       | 9.5E-11 |         |            | 10.02 |         |      |
|        |            | iii      | 7.2E-11 |         |            | 10.14 |         |      |
|        |            | iv       | 5.7E-11 |         |            | 10.24 |         |      |
|        | 4C1I       | i        | 1.0E-10 | 1.2E-10 | 1.9E-11    | 9.98  | 9.93    | 0.07 |
|        |            | ii       | 1.1E-10 |         |            | 9.97  |         |      |
|        |            | iii      | 1.2E-10 |         |            | 9.93  |         |      |
|        |            | iv       | 1.5E-10 |         |            | 9.84  |         |      |
|        | 4C2I       | i        | 1.3E-10 | 1.4E-10 | 3.2E-11    | 9.89  | 9.86    | 0.10 |
|        |            | ii       | 1.3E-10 |         |            | 9.88  |         |      |
|        |            | iii      | 1.1E-10 |         |            | 9.96  |         |      |
|        |            | iv       | 1.8E-10 |         |            | 9.73  |         |      |
| 4CI    | i          | 7.5E-11  | 1.0E-10 | 2.9E-11 | 10.12      | 9.99  | 0.12    |      |
|        | ii         | 8.7E-11  |         |         | 10.06      |       |         |      |
|        | iii        | 1.0E-10  |         |         | 9.99       |       |         |      |
|        | iv         | 1.4E-10  |         |         | 9.85       |       |         |      |

| Sample |      | Sample no. | k (m/s)  |         |         | OPI        |       |         |
|--------|------|------------|----------|---------|---------|------------|-------|---------|
|        |      |            | Measured | Mean    | Std Dev | Calculated | Mean  | Std Dev |
| 4F     | 4FW  | i          | 1.3E-11  | 2.3E-11 | 1.2E-11 | 10.89      | 10.64 | 0.23    |
|        |      | ii         | 3.8E-11  |         |         | 10.42      |       |         |
|        |      | iii        | 2.7E-11  |         |         | 10.56      |       |         |
|        |      | iv         | 1.4E-11  |         |         | 10.86      |       |         |
|        | 4FH  | i          | 2.0E-11  | 2.5E-11 | 4.6E-12 | 10.71      | 10.60 | 0.08    |
|        |      | ii         | 3.0E-11  |         |         | 10.52      |       |         |
|        |      | iii        | 2.7E-11  |         |         | 10.57      |       |         |
|        |      | iv         | 2.4E-11  |         |         | 10.63      |       |         |
|        | 4FO  | i          | 6.5E-11  | 7.8E-11 | 1.3E-11 | 10.18      | 10.11 | 0.07    |
|        |      | ii         | 9.5E-11  |         |         | 10.02      |       |         |
|        |      | iii        | 7.0E-11  |         |         | 10.15      |       |         |
|        |      | iv         | 7.9E-11  |         |         | 10.10      |       |         |
|        | 4F10 | i          | 6.8E-11  | 9.0E-11 | 4.4E-11 | 10.17      | 10.04 | 0.18    |
|        |      | ii         | 6.6E-11  |         |         | 10.18      |       |         |
|        |      | iii        | 7.1E-11  |         |         | 10.15      |       |         |
|        |      | iv         | 1.6E-10  |         |         | 9.81       |       |         |
|        | 4F20 | i          | 1.1E-10  | 1.0E-10 | 1.1E-11 | 9.96       | 9.98  | 0.05    |
|        |      | ii         | 9.4E-11  |         |         | 10.03      |       |         |
|        |      | iii        | 1.2E-10  |         |         | 9.93       |       |         |
|        |      | iv         | 9.6E-11  |         |         | 10.02      |       |         |
|        | 4FC  | i          | 3.9E-11  | 1.5E-10 | 1.7E-11 | 10.41      | 9.84  | 0.05    |
|        |      | ii         | 1.6E-10  |         |         | 9.80       |       |         |
|        |      | iii        | 1.3E-10  |         |         | 9.90       |       |         |
|        |      | iv         | 1.5E-10  |         |         | 9.82       |       |         |
|        | 4F1I | i          | 1.7E-10  | 1.5E-10 | 2.4E-11 | 9.76       | 9.81  | 0.07    |
|        |      | ii         | 1.6E-10  |         |         | 9.80       |       |         |
|        |      | iii        | 1.6E-10  |         |         | 9.79       |       |         |
|        |      | iv         | 1.2E-10  |         |         | 9.93       |       |         |
| 4F2I   | i    | 8.6E-11    | 2.1E-10  | 2.9E-11 | 10.07   | 9.69       | 0.06  |         |
|        | ii   | 2.1E-10    |          |         | 9.68    |            |       |         |
|        | iii  | 2.3E-10    |          |         | 9.63    |            |       |         |
|        | iv   | 1.8E-10    |          |         | 9.75    |            |       |         |
| 4FI    | i    | 1.8E-10    | 1.8E-10  | 5.3E-11 | 9.75    | 9.74       | 0.12  |         |
|        | ii   | 2.6E-10    |          |         | 9.59    |            |       |         |
|        | iii  | 1.4E-10    |          |         | 9.84    |            |       |         |
|        | iv   | 1.5E-10    |          |         | 9.82    |            |       |         |

| Sample |      | Sample no. | k (m/s)  |         |         | OPI        |       |         |
|--------|------|------------|----------|---------|---------|------------|-------|---------|
|        |      |            | Measured | Mean    | Std Dev | Calculated | Mean  | Std Dev |
| 4G     | 4GW  | i          | 1.6E-11  | 5.3E-11 | 5.0E-11 | 10.80      | 10.28 | 0.37    |
|        |      | ii         | 5.4E-11  |         |         | 10.27      |       |         |
|        |      | iii        | 1.2E-10  |         |         | 9.91       |       |         |
|        |      | iv         | 1.9E-11  |         |         | 10.72      |       |         |
|        | 4GH  | i          | 4.1E-11  | 5.2E-11 | 8.3E-12 | 10.38      | 10.28 | 0.07    |
|        |      | ii         | 5.2E-11  |         |         | 10.28      |       |         |
|        |      | iii        | 6.2E-11  |         |         | 10.21      |       |         |
|        |      | iv         | 5.3E-11  |         |         | 10.28      |       |         |
|        | 4GO  | i          | 1.6E-10  | 1.6E-10 | 3.7E-11 | 9.80       | 9.79  | 0.10    |
|        |      | ii         | 1.2E-10  |         |         | 9.90       |       |         |
|        |      | iii        | 6.2E-10  |         |         | 9.21       |       |         |
|        |      | iv         | 2.0E-10  |         |         | 9.70       |       |         |
|        | 4G10 | i          | 1.4E-10  | 1.6E-10 | 3.0E-11 | 9.86       | 9.79  | 0.08    |
|        |      | ii         | 2.0E-10  |         |         | 9.71       |       |         |
|        |      | iii        | 1.6E-10  |         |         | 9.81       |       |         |
|        |      | iv         | 4.3E-10  |         |         | 9.37*      |       |         |
|        | 4G20 | i          | 4.7E-10  | 3.4E-10 | 1.3E-10 | 9.33       | 9.47  | 0.19    |
|        |      | ii         | 2.0E-10  |         |         | 9.69       |       |         |
|        |      | iii        | 9.4E-11  |         |         | 10.03      |       |         |
|        |      | iv         | 3.6E-10  |         |         | 9.45       |       |         |
|        | 4GC  | i          | 6.4E-10  | 4.8E-10 | 1.4E-10 | 9.19       | 9.32  | 0.13    |
|        |      | ii         | 4.6E-10  |         |         | 9.34       |       |         |
|        |      | iii        | 9.5E-11  |         |         | 10.02      |       |         |
|        |      | iv         | 3.5E-10  |         |         | 9.45       |       |         |
|        | 4G1I | i          | 4.7E-10  | 3.9E-10 | 1.2E-10 | 9.33       | 9.41  | 0.16    |
|        |      | ii         | 3.7E-10  |         |         | 9.43       |       |         |
|        |      | iii        | 2.2E-10  |         |         | 9.66       |       |         |
|        |      | iv         | 4.9E-10  |         |         | 9.31       |       |         |
| 4G2I   | i    | 7.4E-10    | 6.0E-10  | 1.5E-10 | 9.13    | 9.22       | 0.11  |         |
|        | ii   | 5.1E-10    |          |         | 9.29    |            |       |         |
|        | iii  | 7.1E-10    |          |         | 9.15    |            |       |         |
|        | iv   | 4.3E-10    |          |         | 9.36    |            |       |         |
| 4GI    | i    | 6.1E-10    | 7.1E-10  | 1.4E-10 | 9.21    | 9.15       | 0.08  |         |
|        | ii   | 7.5E-10    |          |         | 9.12    |            |       |         |
|        | iii  | 5.9E-10    |          |         | 9.23    |            |       |         |
|        | iv   | 8.9E-10    |          |         | 9.05    |            |       |         |

| Sample | Sample no. | k (m/s)  |         |         | OPI        |       |         |      |
|--------|------------|----------|---------|---------|------------|-------|---------|------|
|        |            | Measured | Mean    | Std Dev | Calculated | Mean  | Std Dev |      |
| 4S     | 4SW        | i        | 1.6E-11 | 2.4E-11 | 5.9E-12    | 10.80 | 10.63   | 0.12 |
|        |            | ii       | 2.9E-11 |         |            | 10.54 |         |      |
|        |            | iii      | 2.2E-11 |         |            | 10.65 |         |      |
|        |            | iv       | 2.8E-11 |         |            | 10.55 |         |      |
|        | 4SH        | i        | 5.5E-11 | 5.7E-11 | 1.3E-11    | 10.26 | 10.24   | 0.10 |
|        |            | ii       | 7.4E-11 |         |            | 10.13 |         |      |
|        |            | iii      | 5.9E-11 |         |            | 10.23 |         |      |
|        |            | iv       | 4.1E-11 |         |            | 10.38 |         |      |
|        | 4SO        | i        | 6.3E-11 | 5.3E-11 | 9.7E-12    | 10.20 | 10.28   | 0.08 |
|        |            | ii       | 5.9E-11 |         |            | 10.23 |         |      |
|        |            | iii      | 4.8E-11 |         |            | 10.32 |         |      |
|        |            | iv       | 4.2E-11 |         |            | 10.37 |         |      |
|        | 4SC        | i        | 3.4E-11 | 4.6E-11 | 8.2E-12    | 10.47 | 10.34   | 0.09 |
|        |            | ii       | 4.8E-11 |         |            | 10.32 |         |      |
|        |            | iii      | 5.3E-11 |         |            | 10.28 |         |      |
|        |            | iv       | 4.9E-11 |         |            | 10.31 |         |      |
|        | 4S10       | i        | 6.7E-11 | 7.9E-11 | 1.8E-11    | 10.17 | 10.10   | 0.09 |
|        |            | ii       | 1.1E-10 |         |            | 9.97  |         |      |
|        |            | iii      | 6.8E-11 |         |            | 10.17 |         |      |
|        |            | iv       | 7.6E-11 |         |            | 10.12 |         |      |
|        | 4S20       | i        | 6.2E-11 | 7.4E-11 | 1.1E-11    | 10.21 | 10.13   | 0.07 |
|        |            | ii       | 7.3E-11 |         |            | 10.14 |         |      |
|        |            | iii      | 8.9E-11 |         |            | 10.05 |         |      |
|        |            | iv       | 7.3E-11 |         |            | 10.14 |         |      |
|        | 4S11       | i        | 5.7E-11 | 6.3E-11 | 9.8E-12    | 10.24 | 10.20   | 0.07 |
|        |            | ii       | 7.2E-11 |         |            | 10.14 |         |      |
|        |            | iii      | 7.1E-11 |         |            | 10.15 |         |      |
|        |            | iv       | 5.3E-11 |         |            | 10.27 |         |      |
| 4S21   | i          | 6.9E-11  | 7.4E-11 | 1.6E-11 | 10.16      | 10.13 | 0.09    |      |
|        | ii         | 5.9E-11  |         |         | 10.23      |       |         |      |
|        | iii        | 9.7E-11  |         |         | 10.01      |       |         |      |
|        | iv         | 7.0E-11  |         |         | 10.16      |       |         |      |
| 4S1    | i          | 7.2E-11  | 6.4E-11 | 1.0E-11 | 10.14      | 10.19 | 0.07    |      |
|        | ii         | 7.4E-11  |         |         | 10.13      |       |         |      |
|        | iii        | 5.7E-11  |         |         | 10.24      |       |         |      |
|        | iv         | 5.3E-11  |         |         | 10.28      |       |         |      |

| Sample |      | Sample no. | k (m/s)  |         |         | OPI        |       |         |
|--------|------|------------|----------|---------|---------|------------|-------|---------|
|        |      |            | Measured | Mean    | Std Dev | Calculated | Mean  | Std Dev |
| 5C     | 5CW  | i          | 5.1E-11  | 6.8E-11 | 2.3E-11 | 10.29      | 10.17 | 0.13    |
|        |      | ii         | 6.1E-11  |         |         | 10.21      |       |         |
|        |      | iii        | 5.8E-11  |         |         | 10.23      |       |         |
|        |      | iv         | 1.0E-10  |         |         | 9.99       |       |         |
|        | 5CH  | i          | 2.5E-10  | 5.1E-10 | 3.4E-10 | 9.61       | 9.29  | 0.31    |
|        |      | ii         | 2.2E-10  |         |         | 9.66       |       |         |
|        |      | iii        | 9.3E-10  |         |         | 9.03       |       |         |
|        |      | iv         | 6.4E-10  |         |         | 9.20       |       |         |
|        | 5CO  | i          | 6.0E-10  | 1.2E-09 | 7.8E-10 | 9.22       | 8.91  | 0.30    |
|        |      | ii         | 5.3E-10  |         |         | 9.28       |       |         |
|        |      | iii        | 1.7E-09  |         |         | 8.78       |       |         |
|        |      | iv         | 2.1E-09  |         |         | 8.68       |       |         |
|        | 5C10 | i          | 3.9E-10  | 4.7E-10 | 1.3E-10 | 9.41       | 9.33  | 0.12    |
|        |      | ii         | 3.4E-10  |         |         | 9.46       |       |         |
|        |      | iii        | 5.2E-10  |         |         | 9.28       |       |         |
|        |      | iv         | 6.2E-10  |         |         | 9.21       |       |         |
|        | 5C20 | i          | 9.1E-10  | 1.4E-09 | 8.1E-10 | 9.04       | 8.85  | 0.27    |
|        |      | ii         | 6.1E-10  |         |         | 9.22       |       |         |
|        |      | iii        | 1.8E-09  |         |         | 8.74       |       |         |
|        |      | iv         | 2.4E-09  |         |         | 8.63       |       |         |
|        | 5CC  | i          | 5.6E-10  | 6.5E-10 | 2.0E-10 | 9.25       | 9.19  | 0.13    |
|        |      | ii         | 8.8E-10  |         |         | 9.06       |       |         |
|        |      | iii        | 5.0E-10  |         |         | 9.30       |       |         |
|        |      | iv         | 1.9E-10  |         |         | 9.72       |       |         |
|        | 5C1I | i          | 4.1E-10  | 4.8E-10 | 1.0E-10 | 9.39       | 9.32  | 0.09    |
|        |      | ii         | 5.2E-10  |         |         | 9.29       |       |         |
|        |      | iii        | 3.9E-10  |         |         | 9.41       |       |         |
|        |      | iv         | 6.1E-10  |         |         | 9.21       |       |         |
| 5C2I   | i    | 7.1E-10    | 7.1E-10  | 9.8E-11 | 9.15    | 9.15       | 0.06  |         |
|        | ii   | 5.8E-10    |          |         | 9.24    |            |       |         |
|        | iii  | 8.2E-10    |          |         | 9.09    |            |       |         |
|        | iv   | 7.1E-10    |          |         | 9.15    |            |       |         |
| 5CI    | i    | 6.0E-10    | 6.9E-10  | 2.8E-10 | 9.22    | 9.16       | 0.16  |         |
|        | ii   | 6.0E-10    |          |         | 9.22    |            |       |         |
|        | iii  | 4.6E-10    |          |         | 9.33    |            |       |         |
|        | iv   | 1.1E-09    |          |         | 8.96    |            |       |         |

| Sample |      | Sample no. | k (m/s)  |         |         | OPI        |      |         |
|--------|------|------------|----------|---------|---------|------------|------|---------|
|        |      |            | Measured | Mean    | Std Dev | Calculated | Mean | Std Dev |
| 6C     | 6CW  | i          | 1.8E-10  | 2.0E-10 | 7.1E-11 | 9.74       | 9.70 | 0.16    |
|        |      | ii         | 2.2E-10  |         |         | 9.66       |      |         |
|        |      | iii        | 1.2E-10  |         |         | 9.93       |      |         |
|        |      | iv         | 2.9E-10  |         |         | 9.54       |      |         |
|        | 6CH  | i          | 1.7E-09  | 2.0E-09 | 4.6E-10 | 8.77       | 8.69 | 0.09    |
|        |      | ii         | 1.9E-09  |         |         | 8.73       |      |         |
|        |      | iii        | 6.3E-10  |         |         | 9.20       |      |         |
|        |      | iv         | 2.6E-09  |         |         | 8.59       |      |         |
|        | 6CO  | i          | 2.1E-09  | 1.3E-09 | 8.1E-10 | 8.68       | 8.88 | 0.30    |
|        |      | ii         | 7.1E-10  |         |         | 9.15       |      |         |
|        |      | iii        | 5.3E-10  |         |         | 9.27       |      |         |
|        |      | iv         | 1.9E-09  |         |         | 8.71       |      |         |
|        | 6C10 | i          | 3.8E-09  | 2.0E-09 | 1.4E-09 | 8.42       | 8.70 | 0.31    |
|        |      | ii         | 2.3E-09  |         |         | 8.64       |      |         |
|        |      | iii        | 7.6E-10  |         |         | 9.12       |      |         |
|        |      | iv         | 1.1E-09  |         |         | 8.96       |      |         |
|        | 6C20 | i          | 2.8E-09  | 6.2E-10 | 1.3E-10 | 8.55       | 9.21 | 0.10    |
|        |      | ii         | 6.5E-10  |         |         | 9.19       |      |         |
|        |      | iii        | 4.8E-10  |         |         | 9.32       |      |         |
|        |      | iv         | 7.4E-10  |         |         | 9.13       |      |         |
|        | 6CC  | i          | 1.6E-09  | 1.8E-09 | 6.2E-10 | 8.80       | 8.76 | 0.14    |
|        |      | ii         | 2.7E-09  |         |         | 8.57       |      |         |
|        |      | iii        | 1.4E-09  |         |         | 8.87       |      |         |
|        |      | iv         | 1.4E-09  |         |         | 8.85       |      |         |
|        | 6C1I | i          | 1.7E-09  | 1.9E-09 | 7.6E-10 | 8.76       | 8.71 | 0.19    |
|        |      | ii         | 2.9E-09  |         |         | 8.55       |      |         |
|        |      | iii        | 2.2E-09  |         |         | 8.67       |      |         |
|        |      | iv         | 1.0E-09  |         |         | 8.98       |      |         |
| 6C2I   | i    | 1.9E-09    | 3.0E-09  | 1.0E-09 | 8.73    | 8.52       | 0.16 |         |
|        | ii   | 8.1E-10    |          |         | 9.09    |            |      |         |
|        | iii  | 3.8E-09    |          |         | 8.42    |            |      |         |
|        | iv   | 3.3E-09    |          |         | 8.48    |            |      |         |
| 6CI    | i    | 4.3E-09    | 3.6E-09  | 1.0E-09 | 8.37    | 8.45       | 0.15 |         |
|        | ii   | 4.2E-09    |          |         | 8.38    |            |      |         |
|        | iii  | 3.7E-09    |          |         | 8.43    |            |      |         |
|        | iv   | 2.1E-09    |          |         | 8.68    |            |      |         |

| Sample |      | Sample no. | k (m/s)  |         |         | OPI        |       |         |
|--------|------|------------|----------|---------|---------|------------|-------|---------|
|        |      |            | Measured | Mean    | Std Dev | Calculated | Mean  | Std Dev |
| 4CP    | 4CWP | i          | 1.5E-11  | 1.4E-11 | 6.9E-13 | 10.83      | 10.86 | 0.02    |
|        |      | ii         | 1.4E-11  |         |         | 10.86      |       |         |
|        |      | iii        | 1.3E-11  |         |         | 10.88      |       |         |
|        |      | iv         | 1.4E-11  |         |         | 10.87      |       |         |
|        | 4CIP | i          | 1.6E-10  | 1.6E-10 | 3.8E-11 | 9.78       | 9.79  | 0.10    |
|        |      | ii         | 1.3E-10  |         |         | 9.90       |       |         |
|        |      | iii        | 2.1E-10  |         |         | 9.67       |       |         |
|        |      | iv         | 1.4E-10  |         |         | 9.85       |       |         |
| 4FP    | 4FWP | i          | 1.7E-11  | 1.3E-11 | 3.6E-12 | 10.76      | 10.88 | 0.13    |
|        |      | ii         | 1.5E-11  |         |         | 10.84      |       |         |
|        |      | iii        | 8.7E-12  |         |         | 11.06      |       |         |
|        |      | iv         | 1.3E-11  |         |         | 10.90      |       |         |
|        | 4FIP | i          | 1.6E-10  | 1.4E-10 | 1.2E-11 | 9.79       | 9.84  | 0.03    |
|        |      | ii         | 1.3E-10  |         |         | 9.87       |       |         |
|        |      | iii        | 1.4E-10  |         |         | 9.86       |       |         |
|        |      | iv         | 1.4E-10  |         |         | 9.85       |       |         |
| 4GP    | 4GWP | i          | 5.1E-11  | 1.6E-11 | 4.5E-12 | 10.29      | 10.79 | 0.12    |
|        |      | ii         | 2.1E-11  |         |         | 10.67      |       |         |
|        |      | iii        | 1.3E-11  |         |         | 10.90      |       |         |
|        |      | iv         | 1.5E-11  |         |         | 10.82      |       |         |
|        | 4GIP | i          | 4.6E-10  | 4.5E-10 | 1.5E-11 | 9.34       | 9.35  | 0.01    |
|        |      | ii         | 4.6E-10  |         |         | 9.34       |       |         |
|        |      | iii        | 9.5E-10  |         |         | 9.02       |       |         |
|        |      | iv         | 4.3E-10  |         |         | 9.36       |       |         |
| 4SP    | 4SWP | i          | 3.7E-11  | 4.0E-11 | 3.1E-12 | 10.43      | 10.40 | 0.03    |
|        |      | ii         | 4.4E-11  |         |         | 10.36      |       |         |
|        |      | iii        | 3.7E-11  |         |         | 10.43      |       |         |
|        |      | iv         | 4.1E-11  |         |         | 10.39      |       |         |
|        | 4SIP | i          | 6.0E-11  | 6.9E-11 | 1.4E-11 | 10.22      | 10.16 | 0.08    |
|        |      | ii         | 6.6E-11  |         |         | 10.18      |       |         |
|        |      | iii        | 9.0E-11  |         |         | 10.05      |       |         |
|        |      | iv         | 6.0E-11  |         |         | 10.22      |       |         |
| 5CP    | 5CWP | i          | 4.3E-11  | 5.3E-11 | 9.9E-12 | 10.37      | 10.28 | 0.08    |
|        |      | ii         | 6.3E-11  |         |         | 10.20      |       |         |
|        |      | iii        | 5.3E-11  |         |         | 10.28      |       |         |
|        |      | iv         | 1.5E-10  |         |         | 9.81       |       |         |
|        | 5CIP | i          | 4.0E-10  | 3.0E-10 | 9.1E-11 | 9.40       | 9.53  | 0.14    |
|        |      | ii         | 3.2E-10  |         |         | 9.49       |       |         |
|        |      | iii        | 1.8E-10  |         |         | 9.74       |       |         |
|        |      | iv         | 2.8E-10  |         |         | 9.56       |       |         |

| Sample |      | Sample no. | k (m/s)  |         |         | OPI        |       |         |
|--------|------|------------|----------|---------|---------|------------|-------|---------|
|        |      |            | Measured | Mean    | Std Dev | Calculated | Mean  | Std Dev |
| 4CX    | 4CWX | i          | 1.7E-11  | 2.0E-11 | 5.3E-12 | 10.78      | 10.70 | 0.11    |
|        |      | ii         | 2.7E-11  |         |         | 10.57      |       |         |
|        |      | iii        | 1.6E-11  |         |         | 10.81      |       |         |
|        |      | iv         | 2.0E-11  |         |         | 10.70      |       |         |
|        | 4CIX | i          | 6.0E-11  | 4.7E-11 | 1.2E-11 | 10.23      | 10.33 | 0.11    |
|        |      | ii         | 9.8E-11  |         |         | 10.01*     |       |         |
|        |      | iii        | 4.5E-11  |         |         | 10.35      |       |         |
|        |      | iv         | 3.6E-11  |         |         | 10.45      |       |         |
| 4FX    | 4FWX | i          | 2.1E-11  | 1.4E-11 | 5.2E-12 | 10.67      | 10.84 | 0.15    |
|        |      | ii         | 1.5E-11  |         |         | 10.83      |       |         |
|        |      | iii        | 9.3E-12  |         |         | 11.03      |       |         |
|        |      | iv         | 1.2E-11  |         |         | 10.90      |       |         |
|        | 4FIX | i          | 8.0E-11  | 9.5E-11 | 1.5E-11 | 10.10      | 10.02 | 0.06    |
|        |      | ii         | 9.1E-11  |         |         | 10.04      |       |         |
|        |      | iii        | 9.4E-11  |         |         | 10.03      |       |         |
|        |      | iv         | 1.1E-10  |         |         | 9.94       |       |         |
| 4GX    | 4GWX | i          | 1.4E-11  | 1.3E-11 | 2.2E-12 | 10.84      | 10.87 | 0.08    |
|        |      | ii         | 1.4E-11  |         |         | 10.84      |       |         |
|        |      | iii        | 1.0E-11  |         |         | 10.99      |       |         |
|        |      | iv         | 1.5E-11  |         |         | 10.83      |       |         |
|        | 4GIX | i          | 1.6E-10  | 1.4E-10 | 2.3E-11 | 9.78       | 9.85  | 0.07    |
|        |      | ii         | 1.3E-10  |         |         | 9.87       |       |         |
|        |      | iii        | 1.2E-10  |         |         | 9.94       |       |         |
|        |      | iv         | 1.6E-10  |         |         | 9.80       |       |         |
| 4SX    | 4SWX | i          | 1.9E-11  | 1.7E-11 | 3.1E-12 | 10.72      | 10.78 | 0.09    |
|        |      | ii         | 1.9E-11  |         |         | 10.72      |       |         |
|        |      | iii        | 1.3E-11  |         |         | 10.90      |       |         |
|        |      | iv         | 1.6E-11  |         |         | 10.81      |       |         |
|        | 4SIX | i          | 3.0E-11  | 4.2E-11 | 8.5E-12 | 10.52      | 10.38 | 0.09    |
|        |      | ii         | 5.0E-11  |         |         | 10.30      |       |         |
|        |      | iii        | 4.0E-11  |         |         | 10.40      |       |         |
|        |      | iv         | 4.7E-11  |         |         | 10.33      |       |         |
| 5CX    | 5CWX | i          | 2.2E-11  | 2.4E-11 | 2.2E-12 | 10.67      | 10.62 | 0.04    |
|        |      | ii         | 2.3E-11  |         |         | 10.63      |       |         |
|        |      | iii        | 2.5E-11  |         |         | 10.61      |       |         |
|        |      | iv         | 2.7E-11  |         |         | 10.57      |       |         |
|        | 5CIX | i          | 5.8E-11  | 6.7E-11 | 1.6E-11 | 10.23      | 10.17 | 0.11    |
|        |      | ii         | 8.3E-11  |         |         | 10.08      |       |         |
|        |      | iii        | 7.8E-11  |         |         | 10.11      |       |         |
|        |      | iv         | 4.9E-11  |         |         | 10.31      |       |         |

## Appendix E - Permeability Results (k)

|                      | 4C      | 4F      | 4G      | 4S      | 5C      | 6C      |
|----------------------|---------|---------|---------|---------|---------|---------|
| Water - Untreated    | 3.1E-11 | 2.3E-11 | 5.3E-11 | 2.4E-11 | 6.8E-11 | 2.0E-10 |
| Water - PRA1         | 2.0E-11 | 1.4E-11 | 1.3E-11 | 1.7E-11 | 2.4E-11 | -       |
| Water - PRA2         | 1.4E-11 | 1.3E-11 | 1.6E-11 | 4.0E-11 | 5.3E-11 | -       |
| Winter - Untreated   | 4.5E-11 | 7.8E-11 | 1.6E-10 | 5.3E-11 | 1.2E-09 | 1.3E-09 |
| Winter - CC 1        | 6.8E-11 | 9.0E-11 | 1.6E-10 | 7.9E-11 | 4.7E-10 | 2.0E-09 |
| Winter - CC 2        | 8.0E-11 | 1.0E-10 | 3.4E-10 | 7.4E-11 | 1.4E-09 | 6.2E-10 |
| "Summer" - Untreated | 1.0E-10 | 1.8E-10 | 7.1E-10 | 6.4E-11 | 6.9E-10 | 3.6E-09 |
| "Summer" - Hessian   | 3.8E-11 | 2.5E-11 | 5.2E-11 | 5.7E-11 | 5.1E-10 | 2.0E-09 |
| "Summer" - Clingwrap | 5.9E-11 | 1.5E-10 | 4.8E-10 | 4.6E-11 | 6.5E-10 | 1.8E-09 |
| "Summer" - CC 1      | 1.2E-10 | 1.5E-10 | 3.9E-10 | 6.3E-11 | 4.8E-10 | 1.9E-09 |
| "Summer" - CC 2      | 1.4E-10 | 2.1E-10 | 6.0E-10 | 7.4E-11 | 7.1E-10 | 3.0E-09 |
| "Summer" - PRA1      | 4.7E-11 | 9.5E-11 | 1.4E-10 | 4.2E-11 | 6.7E-11 | -       |
| "Summer" - PRA2      | 1.6E-10 | 1.4E-10 | 4.5E-10 | 6.9E-11 | 3.0E-10 | -       |

## Appendix F - WSI Results

| Sample | Sample no. | Sorptivity              | Ave. Sorptivity         | Std Dev                 | Porosity | Ave. Porosity | Std Dev |     |
|--------|------------|-------------------------|-------------------------|-------------------------|----------|---------------|---------|-----|
|        |            | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (%)      | (%)           | (%)     |     |
| 4C     | 4C1I       | i                       | 9.1                     | 8.5                     | 1.0      | 10.8          | 11.0    | 0.4 |
|        |            | ii                      | 7.5                     |                         |          | 10.4          |         |     |
|        |            | iii                     | 8.0                     |                         |          | 11.2          |         |     |
|        |            | iv                      | 9.6                     |                         |          | 11.4          |         |     |
|        | 4C1O       | i                       | 6.0                     | 5.7                     | 0.4      | 10.0          | 9.8     | 0.4 |
|        |            | ii                      | 5.1                     |                         |          | 9.8           |         |     |
|        |            | iii                     | 5.6                     |                         |          | 9.2           |         |     |
|        |            | iv                      | 5.9                     |                         |          | 10.2          |         |     |
|        | 4C2I       | i                       | 8.0                     | 7.8                     | 0.6      | 10.1          | 9.7     | 0.6 |
|        |            | ii                      | 8.3                     |                         |          | 10.1          |         |     |
|        |            | iii                     | 7.7                     |                         |          | 10.0          |         |     |
|        |            | iv                      | 7.0                     |                         |          | 8.8           |         |     |
|        | 4C2O       | i                       | 5.4                     | 5.8                     | 0.6      | 9.4           | 8.8     | 0.5 |
|        |            | ii                      | 6.0                     |                         |          | 8.9           |         |     |
|        |            | iii                     | 6.5                     |                         |          | 8.9           |         |     |
|        |            | iv                      | 5.3                     |                         |          | 8.2           |         |     |
|        | 4CW        | i                       | 5.9                     | 6.2                     | 0.4      | 9.3           | 8.4     | 0.6 |
|        |            | ii                      | 6.4                     |                         |          | 7.9           |         |     |
|        |            | iii                     | 6.6                     |                         |          | 8.0           |         |     |
|        |            | iv                      | 5.7                     |                         |          | 8.3           |         |     |
|        | 4CI        | i                       | 7.1                     | 8.2                     | 1.1      | 10.3          | 10.5    | 0.4 |
|        |            | ii                      | 7.5                     |                         |          | 10.8          |         |     |
|        |            | iii                     | 9.0                     |                         |          | 10.9          |         |     |
|        |            | iv                      | 9.4                     |                         |          | 10.0          |         |     |
|        | 4CO        | i                       | 5.6                     | 5.6                     | 0.4      | 9.0           | 9.2     | 0.5 |
|        |            | ii                      | 6.0                     |                         |          | 10.0          |         |     |
|        |            | iii                     | 5.8                     |                         |          | 9.0           |         |     |
|        |            | iv                      | 5.1                     |                         |          | 9.1           |         |     |
| 4CH    | i          | 7.0                     | 6.6                     | 0.4                     | 9.1      | 8.6           | 0.3     |     |
|        | ii         | 6.7                     |                         |                         | 8.5      |               |         |     |
|        | iii        | 6.1                     |                         |                         | 8.4      |               |         |     |
|        | iv         | 6.6                     |                         |                         | 8.4      |               |         |     |
| 4CC    | i          | 7.0                     | 6.8                     | 0.4                     | 9.7      | 9.4           | 0.4     |     |
|        | ii         | 6.3                     |                         |                         | 9.0      |               |         |     |
|        | iii        | 7.0                     |                         |                         | 9.2      |               |         |     |
|        | iv         | 7.1                     |                         |                         | 9.8      |               |         |     |

| Sample | Sample no. | Sorptivity              | Ave. Sorptivity         | Std Dev                 | Porosity | Ave. Porosity | Std Dev |     |
|--------|------------|-------------------------|-------------------------|-------------------------|----------|---------------|---------|-----|
|        |            | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (%)      | (%)           | (%)     |     |
| 4F     | 4F1I       | i                       | 10.1                    | 9.5                     | 0.8      | 10.3          | 9.6     | 0.5 |
|        |            | ii                      | 9.5                     |                         |          | 9.5           |         |     |
|        |            | iii                     | 10.1                    |                         |          | 9.6           |         |     |
|        |            | iv                      | 8.3                     |                         |          | 9.1           |         |     |
|        | 4F1O       | i                       | 7.1                     | 6.8                     | 0.7      | 9.1           | 8.7     | 0.4 |
|        |            | ii                      | 6.3                     |                         |          | 8.1           |         |     |
|        |            | iii                     | 6.0                     |                         |          | 8.6           |         |     |
|        |            | iv                      | 7.6                     |                         |          | 8.8           |         |     |
|        | 4F2I       | i                       | 10.0                    | 10.1                    | 1.1      | 10.3          | 10.0    | 0.3 |
|        |            | ii                      | 9.8                     |                         |          | 10.2          |         |     |
|        |            | iii                     | 9.1                     |                         |          | 9.9           |         |     |
|        |            | iv                      | 11.6                    |                         |          | 9.6           |         |     |
|        | 4F2O       | i                       | 8.6                     | 8.0                     | 0.5      | 9.1           | 8.6     | 0.4 |
|        |            | ii                      | 7.6                     |                         |          | 8.4           |         |     |
|        |            | iii                     | 8.3                     |                         |          | 8.8           |         |     |
|        |            | iv                      | 7.6                     |                         |          | 8.2           |         |     |
|        | 4FW        | i                       | 6.7                     | 7.5                     | 0.7      | 5.9           | 5.9     | 0.1 |
|        |            | ii                      | 8.4                     |                         |          | 6.1           |         |     |
|        |            | iii                     | 7.4                     |                         |          | 5.8           |         |     |
|        |            | iv                      | 7.5                     |                         |          | 5.8           |         |     |
|        | 4FI        | i                       | 12.1                    | 12.2                    | 1.8      | 11.4          | 10.6    | 0.6 |
|        |            | ii                      | 14.7                    |                         |          | 10.7          |         |     |
|        |            | iii                     | 11.3                    |                         |          | 10.3          |         |     |
|        |            | iv                      | 10.5                    |                         |          | 10.1          |         |     |
|        | 4FO        | i                       | 6.7                     | 7.4                     | 0.5      | 8.8           | 8.9     | 0.3 |
|        |            | ii                      | 7.8                     |                         |          | 9.3           |         |     |
|        |            | iii                     | 7.7                     |                         |          | 8.9           |         |     |
|        |            | iv                      | 7.3                     |                         |          | 8.7           |         |     |
| 4FH    | i          | 8.6                     | 8.1                     | 0.5                     | 8.3      | 7.9           | 0.9     |     |
|        | ii         | 7.3                     |                         |                         | 8.8      |               |         |     |
|        | iii        | 8.1                     |                         |                         | 7.6      |               |         |     |
|        | iv         | 8.2                     |                         |                         | 6.8      |               |         |     |
| 4FC    | i          | 7.5                     | 8.9                     | 1.1                     | 8.6      | 8.5           | 0.4     |     |
|        | ii         | 9.5                     |                         |                         | 7.8      |               |         |     |
|        | iii        | 8.4                     |                         |                         | 8.7      |               |         |     |
|        | iv         | 10.0                    |                         |                         | 8.7      |               |         |     |

| Sample | Sample no. | Sorptivity              | Ave. Sorptivity         | Std Dev                 | Porosity | Ave. Porosity | Std Dev |     |
|--------|------------|-------------------------|-------------------------|-------------------------|----------|---------------|---------|-----|
|        |            | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (%)      | (%)           | (%)     |     |
| 4G     | 4G1I       | i                       | 11.3                    | 10.6                    | 0.6      | 7.7           | 8.8     | 1.0 |
|        |            | ii                      | 10.4                    |                         |          | 8.3           |         |     |
|        |            | iii                     | 10.0                    |                         |          | 9.9           |         |     |
|        |            | iv                      | 10.5                    |                         |          | 9.4           |         |     |
|        | 4G10       | i                       | 7.5                     | 8.9                     | 1.3      | 7.7           | 8.3     | 0.5 |
|        |            | ii                      | 10.0                    |                         |          | 8.3           |         |     |
|        |            | iii                     | 7.9                     |                         |          | 8.5           |         |     |
|        |            | iv                      | 10.0                    |                         |          | 8.7           |         |     |
|        | 4G2I       | i                       | 13.7                    | 12.7                    | 0.9      | 8.9           | 9.6     | 0.6 |
|        |            | ii                      | 12.7                    |                         |          | 9.9           |         |     |
|        |            | iii                     | 12.8                    |                         |          | 10.3          |         |     |
|        |            | iv                      | 11.6                    |                         |          | 9.2           |         |     |
|        | 4G20       | i                       | 8.4                     | 8.6                     | 0.8      | 8.0           | 8.8     | 0.6 |
|        |            | ii                      | 7.5                     |                         |          | 9.4           |         |     |
|        |            | iii                     | 9.1                     |                         |          | 8.8           |         |     |
|        |            | iv                      | 9.4                     |                         |          | 9.2           |         |     |
|        | 4GW        | i                       | 8.7                     | 8.8                     | 1.5      | 5.8           | 5.7     | 0.2 |
|        |            | ii                      | 10.9                    |                         |          | 5.5           |         |     |
|        |            | iii                     | 7.5                     |                         |          | 5.9           |         |     |
|        |            | iv                      | 8.1                     |                         |          | 5.8           |         |     |
|        | 4GI        | i                       | 14.3                    | 16.1                    | 1.3      | 10.9          | 11.5    | 0.7 |
|        |            | ii                      | 15.8                    |                         |          | 11.8          |         |     |
|        |            | iii                     | 17.1                    |                         |          | 12.3          |         |     |
|        |            | iv                      | 17.1                    |                         |          | 10.8          |         |     |
|        | 4GO        | i                       | 9.0                     | 10.2                    | 1.9      | 9.1           | 9.0     | 0.4 |
|        |            | ii                      | 8.2                     |                         |          | 8.5           |         |     |
|        |            | iii                     | 12.2                    |                         |          | 9.1           |         |     |
|        |            | iv                      | 11.3                    |                         |          | 9.4           |         |     |
| 4GH    | i          | 9.4                     | 9.4                     | 0.2                     | 6.8      | 6.7           | 0.5     |     |
|        | ii         | 9.3                     |                         |                         | 7.1      |               |         |     |
|        | iii        | 9.6                     |                         |                         | 7.0      |               |         |     |
|        | iv         | 9.3                     |                         |                         | 6.0      |               |         |     |
| 4GC    | i          | 10.9                    | 9.8                     | 1.5                     | 7.3      | 7.3           | 0.1     |     |
|        | ii         | 11.3                    |                         |                         | 7.1      |               |         |     |
|        | iii        | 8.0                     |                         |                         | 7.4      |               |         |     |
|        | iv         | 9.1                     |                         |                         | 7.3      |               |         |     |

| Sample | Sample no. | Sorptivity              | Ave. Sorptivity         | Std Dev                 | Porosity | Ave. Porosity | Std Dev |     |
|--------|------------|-------------------------|-------------------------|-------------------------|----------|---------------|---------|-----|
|        |            | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (%)      | (%)           | (%)     |     |
| 4S     | 4S1I       | i                       | 4.2                     | 4.4                     | 0.3      | 12.1          | 11.7    | 0.6 |
|        |            | ii                      | 4.6                     |                         |          | 12.3          |         |     |
|        |            | iii                     | 4.1                     |                         |          | 11.6          |         |     |
|        |            | iv                      | 4.6                     |                         |          | 11.0          |         |     |
|        | 4S1O       | i                       | 3.8                     | 3.7                     | 0.4      | 12.0          | 12.2    | 0.5 |
|        |            | ii                      | 4.1                     |                         |          | 12.7          |         |     |
|        |            | iii                     | 3.2                     |                         |          | 12.4          |         |     |
|        |            | iv                      | 3.8                     |                         |          | 11.6          |         |     |
|        | 4S2I       | i                       | 4.5                     | 5.0                     | 0.7      | 11.9          | 11.8    | 0.4 |
|        |            | ii                      | 5.7                     |                         |          | 11.2          |         |     |
|        |            | iii                     | 5.5                     |                         |          | 11.9          |         |     |
|        |            | iv                      | 4.3                     |                         |          | 12.2          |         |     |
|        | 4S2O       | i                       | 4.0                     | 4.0                     | 0.3      | 12.8          | 12.3    | 0.5 |
|        |            | ii                      | 4.0                     |                         |          | 12.5          |         |     |
|        |            | iii                     | 4.3                     |                         |          | 11.7          |         |     |
|        |            | iv                      | 3.7                     |                         |          | 12.1          |         |     |
|        | 4SW        | i                       | 3.8                     | 4.6                     | 0.6      | 7.8           | 7.9     | 0.3 |
|        |            | ii                      | 4.5                     |                         |          | 7.7           |         |     |
|        |            | iii                     | 5.3                     |                         |          | 7.7           |         |     |
|        |            | iv                      | 5.0                     |                         |          | 8.4           |         |     |
|        | 4SI        | i                       | 4.9                     | 4.8                     | 0.6      | 12.3          | 11.3    | 0.7 |
|        |            | ii                      | 5.4                     |                         |          | 11.3          |         |     |
|        |            | iii                     | 4.1                     |                         |          | 11.2          |         |     |
|        |            | iv                      | 4.8                     |                         |          | 10.5          |         |     |
|        | 4SO        | i                       | 4.4                     | 4.1                     | 0.4      | 10.2          | 10.6    | 0.5 |
|        |            | ii                      | 4.1                     |                         |          | 10.0          |         |     |
|        |            | iii                     | 4.4                     |                         |          | 11.1          |         |     |
|        |            | iv                      | 3.5                     |                         |          | 10.9          |         |     |
| 4SH    | i          | 4.3                     | 3.9                     | 0.3                     | 10.7     | 10.1          | 1.1     |     |
|        | ii         | 3.9                     |                         |                         | 8.6      |               |         |     |
|        | iii        | 3.6                     |                         |                         | 11.0     |               |         |     |
|        | iv         | 3.8                     |                         |                         | 10.0     |               |         |     |
| 4SC    | i          | 4.5                     | 4.3                     | 0.3                     | 9.7      | 9.9           | 0.1     |     |
|        | ii         | 3.9                     |                         |                         | 9.9      |               |         |     |
|        | iii        | 4.5                     |                         |                         | 10.0     |               |         |     |
|        | iv         | 4.1                     |                         |                         | 10.1     |               |         |     |

| Sample | Sample no. | Sorptivity              | Ave. Sorptivity         | Std Dev                 | Porosity | Ave. Porosity | Std Dev |     |
|--------|------------|-------------------------|-------------------------|-------------------------|----------|---------------|---------|-----|
|        |            | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (%)      | (%)           | (%)     |     |
| 5C     | 5C1I       | i                       | 11.0                    | 11.1                    | 1.2      | 9.5           | 9.8     | 0.6 |
|        |            | ii                      | 10.9                    |                         |          | 9.3           |         |     |
|        |            | iii                     | 12.7                    |                         |          | 10.0          |         |     |
|        |            | iv                      | 9.8                     |                         |          | 10.6          |         |     |
|        | 5C10       | i                       | 12.0                    | 11.3                    | 0.6      | 9.6           | 9.8     | 0.4 |
|        |            | ii                      | 10.7                    |                         |          | 10.3          |         |     |
|        |            | iii                     | 11.6                    |                         |          | 9.7           |         |     |
|        |            | iv                      | 10.9                    |                         |          | 9.5           |         |     |
|        | 5C2I       | i                       | 9.9                     | 12.6                    | 2.2      | 9.7           | 9.4     | 0.4 |
|        |            | ii                      | 15.3                    |                         |          | 9.4           |         |     |
|        |            | iii                     | 12.3                    |                         |          | 8.8           |         |     |
|        |            | iv                      | 12.9                    |                         |          | 9.7           |         |     |
|        | 5C20       | i                       | 12.4                    | 12.6                    | 1.7      | 9.6           | 9.2     | 0.3 |
|        |            | ii                      | 14.9                    |                         |          | 9.0           |         |     |
|        |            | iii                     | 10.8                    |                         |          | 9.3           |         |     |
|        |            | iv                      | 12.4                    |                         |          | 8.9           |         |     |
|        | 5CW        | i                       | 9.0                     | 9.5                     | 0.3      | 7.5           | 8.0     | 0.5 |
|        |            | ii                      | 9.8                     |                         |          | 8.6           |         |     |
|        |            | iii                     | 9.4                     |                         |          | 8.2           |         |     |
|        |            | iv                      | 9.6                     |                         |          | 7.8           |         |     |
|        | 5CI        | i                       | 17.8                    | 14.2                    | 2.5      | 9.3           | 9.4     | 0.4 |
|        |            | ii                      | 12.9                    |                         |          | 9.3           |         |     |
|        |            | iii                     | 12.1                    |                         |          | 9.2           |         |     |
|        |            | iv                      | 14.1                    |                         |          | 10.0          |         |     |
|        | 5CO        | i                       | 10.6                    | 13.2                    | 1.9      | 9.3           | 9.3     | 0.3 |
|        |            | ii                      | 13.6                    |                         |          | 9.7           |         |     |
|        |            | iii                     | 15.0                    |                         |          | 9.2           |         |     |
|        |            | iv                      | 13.4                    |                         |          | 9.0           |         |     |
| 5CH    | i          | 11.4                    | 11.4                    | 0.0                     | 9.7      | 8.4           | 0.9     |     |
|        | ii         | 11.3                    |                         |                         | 8.2      |               |         |     |
|        | iii        | 11.4                    |                         |                         | 8.0      |               |         |     |
|        | iv         | 11.4                    |                         |                         | 7.7      |               |         |     |
| 5CC    | i          | 12.8                    | 12.4                    | 3.1                     | 8.5      | 8.7           | 0.3     |     |
|        | ii         | 16.3                    |                         |                         | 9.0      |               |         |     |
|        | iii        | 11.3                    |                         |                         | 8.4      |               |         |     |
|        | iv         | 9.0                     |                         |                         | 8.9      |               |         |     |

| Sample | Sample no. | Sorptivity              | Ave. Sorptivity         | Std Dev                 | Porosity | Ave. Porosity | Std Dev |     |
|--------|------------|-------------------------|-------------------------|-------------------------|----------|---------------|---------|-----|
|        |            | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (%)      | (%)           | (%)     |     |
| 6C     | 6C1I       | i                       | 17.0                    | 16.9                    | 0.8      | 9.7           | 9.7     | 0.1 |
|        |            | ii                      | 17.8                    |                         |          | 9.7           |         |     |
|        |            | iii                     | 17.0                    |                         |          | 9.7           |         |     |
|        |            | iv                      | 15.9                    |                         |          | 9.9           |         |     |
|        | 6C10       | i                       | 16.5                    | 14.1                    | 1.6      | 9.4           | 9.6     | 0.5 |
|        |            | ii                      | 13.2                    |                         |          | 9.6           |         |     |
|        |            | iii                     | 13.2                    |                         |          | 10.4          |         |     |
|        |            | iv                      | 13.6                    |                         |          | 9.2           |         |     |
|        | 6C2I       | i                       | 15.7                    | 18.0                    | 3.0      | 9.3           | 9.4     | 0.2 |
|        |            | ii                      | 15.1                    |                         |          | 9.4           |         |     |
|        |            | iii                     | 20.9                    |                         |          | 9.7           |         |     |
|        |            | iv                      | 20.3                    |                         |          | 9.4           |         |     |
|        | 6C20       | i                       | 15.9                    | 13.0                    | 2.0      | 9.7           | 10.0    | 0.5 |
|        |            | ii                      | 11.8                    |                         |          | 10.5          |         |     |
|        |            | iii                     | 11.8                    |                         |          | 9.4           |         |     |
|        |            | iv                      | 12.3                    |                         |          | 10.4          |         |     |
|        | 6CW        | i                       | 8.3                     | 8.3                     | 0.6      | 9.6           | 9.6     | 0.2 |
|        |            | ii                      | 8.5                     |                         |          | 9.7           |         |     |
|        |            | iii                     | 8.9                     |                         |          | 9.8           |         |     |
|        |            | iv                      | 7.5                     |                         |          | 9.4           |         |     |
|        | 6CI        | i                       | 20.0                    | 19.1                    | 1.7      | 11.3          | 10.5    | 0.7 |
|        |            | ii                      | 21.0                    |                         |          | 10.7          |         |     |
|        |            | iii                     | 17.9                    |                         |          | 10.2          |         |     |
|        |            | iv                      | 17.4                    |                         |          | 9.8           |         |     |
|        | 6C0        | i                       | 13.6                    | 14.9                    | 4.2      | 10.6          | 10.9    | 0.4 |
|        |            | ii                      | 12.2                    |                         |          | 11.2          |         |     |
|        |            | iii                     | 12.6                    |                         |          | 11.2          |         |     |
|        |            | iv                      | 21.2                    |                         |          | 10.5          |         |     |
| 6CH    | i          | 13.3                    | 13.2                    | 1.6                     | 10.3     | 10.7          | 0.5     |     |
|        | ii         | 12.5                    |                         |                         | 11.1     |               |         |     |
|        | iii        | 11.5                    |                         |                         | 11.1     |               |         |     |
|        | iv         | 15.3                    |                         |                         | 10.2     |               |         |     |
| 6CC    | i          | 16.6                    | 14.7                    | 1.5                     | 10.2     | 10.5          | 0.2     |     |
|        | ii         | 14.7                    |                         |                         | 10.4     |               |         |     |
|        | iii        | 12.8                    |                         |                         | 10.6     |               |         |     |
|        | iv         | 14.8                    |                         |                         | 10.8     |               |         |     |

| Sample |      | Sample no. | Sorptivity              | Ave. Sorptivity         | Std Dev                 | Porosity | Ave. Porosity | Std Dev |
|--------|------|------------|-------------------------|-------------------------|-------------------------|----------|---------------|---------|
|        |      |            | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (mm/hr <sup>0.5</sup> ) | (%)      | (%)           | (%)     |
| 4CP    | 4CWP | i          | 6.2                     | 6.9                     | 0.6                     | 7.4      | 7.2           | 0.1     |
|        |      | ii         | 7.1                     |                         |                         | 7.1      |               |         |
|        |      | iii        | 6.7                     |                         |                         | 7.2      |               |         |
|        |      | iv         | 7.7                     |                         |                         | 7.3      |               |         |
|        | 4CIP | i          | 9.8                     | 8.7                     | 1.0                     | 9.9      | 9.2           | 0.6     |
|        |      | ii         | 8.3                     |                         |                         | 9.4      |               |         |
|        |      | iii        | 9.4                     |                         |                         | 8.4      |               |         |
|        |      | iv         | 7.5                     |                         |                         | 8.9      |               |         |
| 4FP    | 4FWP | i          | 7.1                     | 8.0                     | 0.9                     | 6.2      | 6.5           | 0.6     |
|        |      | ii         | 9.3                     |                         |                         | 6.7      |               |         |
|        |      | iii        | 7.5                     |                         |                         | 7.2      |               |         |
|        |      | iv         | 8.0                     |                         |                         | 5.8      |               |         |
|        | 4FIP | i          | 13.6                    | 12.5                    | 1.0                     | 9.2      | 8.7           | 0.4     |
|        |      | ii         | 12.1                    |                         |                         | 8.9      |               |         |
|        |      | iii        | 11.3                    |                         |                         | 8.8      |               |         |
|        |      | iv         | 12.8                    |                         |                         | 8.2      |               |         |
| 4GP    | 4GWP | i          | 7.3                     | 7.4                     | 1.0                     | 5.3      | 5.5           | 0.4     |
|        |      | ii         | 8.5                     |                         |                         | 5.1      |               |         |
|        |      | iii        | 6.1                     |                         |                         | 5.5      |               |         |
|        |      | iv         | 7.6                     |                         |                         | 6.1      |               |         |
|        | 4GIP | i          | 12.1                    | 12.8                    | 1.1                     | 10.2     | 10.5          | 0.9     |
|        |      | ii         | 13.2                    |                         |                         | 11.5     |               |         |
|        |      | iii        | 14.2                    |                         |                         | 10.9     |               |         |
|        |      | iv         | 11.9                    |                         |                         | 9.5      |               |         |
| 4SP    | 4SWP | i          | 4.1                     | 4.6                     | 0.9                     | 8.9      | 9.1           | 0.3     |
|        |      | ii         | 4.3                     |                         |                         | 9.1      |               |         |
|        |      | iii        | 4.0                     |                         |                         | 9.5      |               |         |
|        |      | iv         | 5.9                     |                         |                         | 8.9      |               |         |
|        | 4SIP | i          | 4.7                     | 5.9                     | 1.1                     | 9.7      | 10.2          | 0.5     |
|        |      | ii         | 5.3                     |                         |                         | 9.8      |               |         |
|        |      | iii        | 6.4                     |                         |                         | 10.8     |               |         |
|        |      | iv         | 7.2                     |                         |                         | 10.5     |               |         |
| 5CP    | 5CWP | i          | 7.4                     | 8.5                     | 1.7                     | 8.7      | 9.1           | 0.2     |
|        |      | ii         | 9.7                     |                         |                         | 9.1      |               |         |
|        |      | iii        | 6.7                     |                         |                         | 9.2      |               |         |
|        |      | iv         | 10.1                    |                         |                         | 9.2      |               |         |
|        | 5CIP | i          | 12.9                    | 12.0                    | 1.7                     | 9.9      | 10.0          | 0.3     |
|        |      | ii         | 13.0                    |                         |                         | 10.0     |               |         |
|        |      | iii        | 9.5                     |                         |                         | 10.4     |               |         |
|        |      | iv         | 12.7                    |                         |                         | 9.6      |               |         |

| Sample |      | Sample no. | Sorptivity<br>(mm/hr <sup>0.5</sup> ) | Ave. Sorptivity<br>(mm/hr <sup>0.5</sup> ) | Std Dev<br>(mm/hr <sup>0.5</sup> ) | Porosity<br>(%) | Ave. Porosity<br>(%) | Std Dev<br>(%) |
|--------|------|------------|---------------------------------------|--|------------------------------------|-----------------|----------------------|----------------|
| 4CX    | 4CWX | i          | 6.9                                   | 6.6  | 1.4                                | 7.8             | 8.1                  | 0.3            |
|        |      | ii         | 8.4                                   |  |                                    | 8.4             |                      |                |
|        |      | iii        | 5.6                                   |  |                                    | 7.9             |                      |                |
|        |      | iv         | 5.5                                   |  |                                    | 8.4             |                      |                |
|        | 4CIX | i          | 7.0                                   | 6.7  | 0.6                                | 9.6             | 9.2                  | 0.4            |
|        |      | ii         | 6.9                                   |  |                                    | 9.5             |                      |                |
|        |      | iii        | 6.9                                   |  |                                    | 8.9             |                      |                |
|        |      | iv         | 5.8                                   |  |                                    | 8.9             |                      |                |
| 4FX    | 4FWX | i          | 7.5                                   | 7.5  | 1.3                                | 5.9             | 6.0                  | 0.1            |
|        |      | ii         | 6.9                                   |  |                                    | 6.1             |                      |                |
|        |      | iii        | 9.3                                   |  |                                    | 6.1             |                      |                |
|        |      | iv         | 6.2                                   |  |                                    | 5.9             |                      |                |
|        | 4FIX | i          | 8.2                                   | 9.5  | 1.2                                | 9.5             | 9.8                  | 0.2            |
|        |      | ii         | 8.9                                   |  |                                    | 9.9             |                      |                |
|        |      | iii        | 10.8                                  |  |                                    | 9.7             |                      |                |
|        |      | iv         | 10.1                                  |  |                                    | 9.9             |                      |                |
| 4GX    | 4GWX | i          | 7.2                                   | 6.4  | 0.5                                | 4.5             | 4.8                  | 0.2            |
|        |      | ii         | 6.3                                   |  |                                    | 4.9             |                      |                |
|        |      | iii        | 6.0                                   |  |                                    | 4.8             |                      |                |
|        |      | iv         | 6.3                                   |  |                                    | 5.0             |                      |                |
|        | 4GIX | i          | 7.3                                   | 8.0  | 0.8                                | 10.1            | 10.0                 | 0.1            |
|        |      | ii         | 8.6                                   |  |                                    | 10.1            |                      |                |
|        |      | iii        | 7.2                                   |  |                                    | 9.8             |                      |                |
|        |      | iv         | 8.8                                   |  |                                    | 10.0            |                      |                |
| 4SX    | 4SWX | i          | 4.5                                   | 4.4  | 0.4                                | 6.2             | 6.2                  | 0.6            |
|        |      | ii         | 4.9                                   |  |                                    | 6.8             |                      |                |
|        |      | iii        | 4.1                                   |  |                                    | 6.4             |                      |                |
|        |      | iv         | 4.0                                   |  |                                    | 5.4             |                      |                |
|        | 4SIX | i          | 4.2                                   | 4.3  | 0.2                                | 9.5             | 9.6                  | 0.1            |
|        |      | ii         | 4.5                                   |  |                                    | 9.7             |                      |                |
|        |      | iii        | 4.3                                   |  |                                    | 9.5             |                      |                |
|        |      | iv         | 4.1                                   |  |                                    | 9.7             |                      |                |
| 5CX    | 5CWX | i          | 5.9                                   | 5.8  | 0.4                                | 9.3             | 9.1                  | 0.2            |
|        |      | ii         | 6.3                                   |  |                                    | 8.9             |                      |                |
|        |      | iii        | 5.4                                   |  |                                    | 9.1             |                      |                |
|        |      | iv         | 5.6                                   |  |                                    | 9.1             |                      |                |
|        | 5CIX | i          | 6.4                                   | 6.2  | 0.3                                | 10.5            | 11.0                 | 0.7            |
|        |      | ii         | 5.9                                   |  |                                    | 11.8            |                      |                |
|        |      | iii        | 6.5                                   |  |                                    | 10.3            |                      |                |
|        |      | iv         | 5.9                                   |  |                                    | 11.3            |                      |                |

## Appendix G - CCI Results

| Sample | Sample no. | Sample Results | Mean    | Std Dev |      |
|--------|------------|----------------|---------|---------|------|
|        |            | (mS/cm)        | (mS/cm) | (mS/cm) |      |
| 4C     | 4C1I       | i              | 0.88    | 0.97    | 0.06 |
|        |            | ii             | 1.02    |         |      |
|        |            | iii            | 0.99    |         |      |
|        |            | iv             | 0.99    |         |      |
|        | 4C1O       | i              | 0.78    | 0.77    | 0.07 |
|        |            | ii             | 0.84    |         |      |
|        |            | iii            | 0.67    |         |      |
|        |            | iv             | 0.78    |         |      |
|        | 4C2I       | i              | 0.99    | 1.00    | 0.07 |
|        |            | ii             | 1.00    |         |      |
|        |            | iii            | 1.08    |         |      |
|        |            | iv             | 0.92    |         |      |
|        | 4C2O       | i              | 0.92    | 0.82    | 0.11 |
|        |            | ii             | 0.89    |         |      |
|        |            | iii            | 0.77    |         |      |
|        |            | iv             | 0.68    |         |      |
|        | 4CW        | i              | 0.78    | 0.72    | 0.05 |
|        |            | ii             | 0.66    |         |      |
|        |            | iii            | 0.69    |         |      |
|        |            | iv             | 0.73    |         |      |
| 4CI    | i          | 1.19           | 1.22    | 0.07    |      |
|        | ii         | 1.15           |         |         |      |
|        | iii        | 1.27           |         |         |      |
|        | iv         | 1.28           |         |         |      |
| 4CO    | i          | 0.82           | 0.92    | 0.08    |      |
|        | ii         | 1.00           |         |         |      |
|        | iii        | 0.89           |         |         |      |
|        | iv         | 0.98           |         |         |      |
| 4CH    | i          | 0.87           | 0.85    | 0.05    |      |
|        | ii         | 0.79           |         |         |      |
|        | iii        | 0.84           |         |         |      |
|        | iv         | 0.89           |         |         |      |
| 4CC    | i          | 1.07           | 1.02    | 0.03    |      |
|        | ii         | 1.01           |         |         |      |
|        | iii        | 1.01           |         |         |      |
|        | iv         | 1.01           |         |         |      |

| Sample | Sample no. | Sample Results | Mean    | Std Dev |      |
|--------|------------|----------------|---------|---------|------|
|        |            | (mS/cm)        | (mS/cm) | (mS/cm) |      |
| 4F     | 4F1I       | i              | 0.94    | 0.91    | 0.05 |
|        |            | ii             | 0.86    |         |      |
|        |            | iii            | 0.96    |         |      |
|        |            | iv             | 0.89    |         |      |
|        | 4F1O       | i              | 0.64    | 0.73    | 0.11 |
|        |            | ii             | 0.88    |         |      |
|        |            | iii            | 0.72    |         |      |
|        |            | iv             | 0.66    |         |      |
|        | 4F2I       | i              | 1.08    | 1.10    | 0.01 |
|        |            | ii             | 1.11    |         |      |
|        |            | iii            | 1.10    |         |      |
|        |            | iv             | 0.85    |         |      |
|        | 4F2O       | i              | 0.63    | 0.84    | 0.17 |
|        |            | ii             | 0.81    |         |      |
|        |            | iii            | 0.86    |         |      |
|        |            | iv             | 1.04    |         |      |
|        | 4FW        | i              | 0.24    | 0.25    | 0.02 |
|        |            | ii             | 0.28    |         |      |
|        |            | iii            | 0.23    |         |      |
|        |            | iv             | 0.25    |         |      |
|        | 4FI        | i              | 0.87    | 0.99    | 0.10 |
|        |            | ii             | 1.02    |         |      |
|        |            | iii            | 1.11    |         |      |
|        |            | iv             | 0.94    |         |      |
|        | 4FO        | i              | 0.56    | 0.62    | 0.04 |
|        |            | ii             | 0.61    |         |      |
|        |            | iii            | 0.65    |         |      |
|        |            | iv             | 0.65    |         |      |
| 4FH    | i          | 0.46           | 0.45    | 0.05    |      |
|        | ii         | 0.51           |         |         |      |
|        | iii        | 0.41           |         |         |      |
|        | iv         | 0.41           |         |         |      |
| 4FC    | i          | 0.60           | 0.60    | 0.03    |      |
|        | ii         | 0.57           |         |         |      |
|        | iii        | 0.63           |         |         |      |
|        | iv         | 0.61           |         |         |      |

| Sample | Sample no. | Sample Results | Mean    | Std Dev |      |
|--------|------------|----------------|---------|---------|------|
|        |            | (mS/cm)        | (mS/cm) | (mS/cm) |      |
| 4G     | 4G1I       | i              | 0.66    | 0.61    | 0.06 |
|        |            | ii             | 0.53    |         |      |
|        |            | iii            | 0.64    |         |      |
|        |            | iv             | 0.59    |         |      |
|        | 4G10       | i              | 0.42    | 0.44    | 0.09 |
|        |            | ii             | 0.41    |         |      |
|        |            | iii            | 0.37    |         |      |
|        |            | iv             | 0.58    |         |      |
|        | 4G2I       | i              | 0.54    | 0.78    | 0.22 |
|        |            | ii             | 0.89    |         |      |
|        |            | iii            | 0.66    |         |      |
|        |            | iv             | 1.02    |         |      |
|        | 4G20       | i              | 0.45    | 0.48    | 0.06 |
|        |            | ii             | 0.49    |         |      |
|        |            | iii            | 0.41    |         |      |
|        |            | iv             | 0.55    |         |      |
|        | 4GW        | i              | 0.23    | 0.23    | 0.01 |
|        |            | ii             | 0.22    |         |      |
|        |            | iii            | 0.25    |         |      |
|        |            | iv             | 0.23    |         |      |
|        | 4GI        | i              | 0.93    | 1.36    | 0.17 |
|        |            | ii             | 1.30    |         |      |
|        |            | iii            | 1.55    |         |      |
|        |            | iv             | 1.23    |         |      |
|        | 4GO        | i              | 0.32    | 0.34    | 0.03 |
|        |            | ii             | 0.37    |         |      |
|        |            | iii            | 0.32    |         |      |
|        |            | iv             | 0.34    |         |      |
| 4GH    | i          | 0.33           | 0.28    | 0.04    |      |
|        | ii         | 0.29           |         |         |      |
|        | iii        | 0.24           |         |         |      |
|        | iv         | 0.27           |         |         |      |
| 4GC    | i          | 0.58           | 0.63    | 0.07    |      |
|        | ii         | 0.47           |         |         |      |
|        | iii        | 0.72           |         |         |      |
|        | iv         | 0.60           |         |         |      |

| Sample | Sample no. | Sample Results | Mean    | Std Dev |      |
|--------|------------|----------------|---------|---------|------|
|        |            | (mS/cm)        | (mS/cm) | (mS/cm) |      |
| 4S     | 4S1I       | i              | 0.75    | 0.80    | 0.07 |
|        |            | ii             | 0.88    |         |      |
|        |            | iii            | 0.85    |         |      |
|        |            | iv             | 0.74    |         |      |
|        | 4S1O       | i              | 0.75    | 0.79    | 0.10 |
|        |            | ii             | 0.69    |         |      |
|        |            | iii            | 0.81    |         |      |
|        |            | iv             | 0.91    |         |      |
|        | 4S2I       | i              | 0.79    | 0.86    | 0.04 |
|        |            | ii             | 0.87    |         |      |
|        |            | iii            | 0.89    |         |      |
|        |            | iv             | 0.87    |         |      |
|        | 4S2O       | i              | 0.75    | 0.78    | 0.06 |
|        |            | ii             | 0.84    |         |      |
|        |            | iii            | 0.71    |         |      |
|        |            | iv             | 0.83    |         |      |
|        | 4SW        | i              | 0.27    | 0.26    | 0.01 |
|        |            | ii             | 0.27    |         |      |
|        |            | iii            | 0.24    |         |      |
|        |            | iv             | 0.25    |         |      |
|        | 4SI        | i              | 0.58    | 0.62    | 0.07 |
|        |            | ii             | 0.55    |         |      |
|        |            | iii            | 0.66    |         |      |
|        |            | iv             | 0.70    |         |      |
|        | 4SO        | i              | 0.43    | 0.48    | 0.03 |
|        |            | ii             | 0.49    |         |      |
|        |            | iii            | 0.51    |         |      |
|        |            | iv             | 0.47    |         |      |
| 4SH    | i          | 0.43           | 0.40    | 0.03    |      |
|        | ii         | 0.35           |         |         |      |
|        | iii        | 0.41           |         |         |      |
|        | iv         | 0.40           |         |         |      |
| 4SC    | i          | 0.37           | 0.38    | 0.04    |      |
|        | ii         | 0.36           |         |         |      |
|        | iii        | 0.44           |         |         |      |
|        | iv         | 0.36           |         |         |      |

| Sample |      | Sample no. | Sample Results | Mean    | Std Dev |
|--------|------|------------|----------------|---------|---------|
|        |      |            | (mS/cm)        | (mS/cm) | (mS/cm) |
| 4CP    | 4CWP | i          | 0.46           | 0.56    | 0.07    |
|        |      | ii         | 0.58           |         |         |
|        |      | iii        | 0.63           |         |         |
|        |      | iv         | 0.58           |         |         |
|        | 4CIP | i          | 1.27           | 1.21    | 0.05    |
|        |      | ii         | 1.16           |         |         |
|        |      | iii        | 0.92           |         |         |
|        |      | iv         | 1.19           |         |         |
| 4FP    | 4FWP | i          | 0.26           | 0.24    | 0.01    |
|        |      | ii         | 0.23           |         |         |
|        |      | iii        | 0.24           |         |         |
|        |      | iv         | 0.23           |         |         |
|        | 4FIP | i          | 1.18           | 1.16    | 0.13    |
|        |      | ii         | 1.28           |         |         |
|        |      | iii        | 1.03           |         |         |
|        |      | iv         | 0.92           |         |         |
| 4GP    | 4GWP | i          | 0.17           | 0.15    | 0.02    |
|        |      | ii         | 0.14           |         |         |
|        |      | iii        | 0.12           |         |         |
|        |      | iv         | 0.15           |         |         |
|        | 4GIP | i          | 1.10           | 1.00    | 0.10    |
|        |      | ii         | 0.93           |         |         |
|        |      | iii        | 0.80           |         |         |
|        |      | iv         | 0.95           |         |         |
| 4SP    | 4SWP | i          | 0.29           | 0.31    | 0.02    |
|        |      | ii         | 0.34           |         |         |
|        |      | iii        | 0.30           |         |         |
|        |      | iv         | 0.30           |         |         |
|        | 4SIP | i          | 0.65           | 0.71    | 0.06    |
|        |      | ii         | 0.77           |         |         |
|        |      | iii        | 0.72           |         |         |
|        |      | iv         | 0.52           |         |         |

| Sample |      | Sample no. | Sample Results | Mean    | Std Dev |
|--------|------|------------|----------------|---------|---------|
|        |      |            | (mS/cm)        | (mS/cm) | (mS/cm) |
| 4CX    | 4CWX | i          | 0.63           | 0.64    | 0.06    |
|        |      | ii         | 0.73           |         |         |
|        |      | iii        | 0.59           |         |         |
|        |      | iv         | 0.63           |         |         |
|        | 4CIX | i          | 0.81           | 0.89    | 0.07    |
|        |      | ii         | 0.99           |         |         |
|        |      | iii        | 0.87           |         |         |
|        |      | iv         | 0.88           |         |         |
| 4FX    | 4FWX | i          | 0.24           | 0.23    | 0.03    |
|        |      | ii         | 0.24           |         |         |
|        |      | iii        | 0.24           |         |         |
|        |      | iv         | 0.19           |         |         |
|        | 4FIX | i          | 0.67           | 0.68    | 0.07    |
|        |      | ii         | 0.64           |         |         |
|        |      | iii        | 0.78           |         |         |
|        |      | iv         | 0.62           |         |         |
| 4GX    | 4GWX | i          | 0.17           | 0.16    | 0.02    |
|        |      | ii         | 0.18           |         |         |
|        |      | iii        | 0.15           |         |         |
|        |      | iv         | 0.15           |         |         |
|        | 4GIX | i          | 0.63           | 0.54    | 0.06    |
|        |      | ii         | 0.51           |         |         |
|        |      | iii        | 0.51           |         |         |
|        |      | iv         | 0.53           |         |         |
| 4SX    | 4SWX | i          | 0.16           | 0.18    | 0.02    |
|        |      | ii         | 0.20           |         |         |
|        |      | iii        | 0.20           |         |         |
|        |      | iv         | 0.17           |         |         |
|        | 4SIX | i          | 0.36           | 0.37    | 0.05    |
|        |      | ii         | 0.31           |         |         |
|        |      | iii        | 0.41           |         |         |
|        |      | iv         | 0.40           |         |         |

## Appendix H - Accelerated Carbonation Results

| Mix | Carbonation Depth (mm) |         |         | Carbonation Coefficient A (mm/√d) |         |         | Ave A (mm/√d) | Std Dev (mm/√d) |
|-----|------------------------|---------|---------|-----------------------------------|---------|---------|---------------|-----------------|
|     | 3 weeks                | 6 weeks | 9 weeks | 3 weeks                           | 6 weeks | 9 weeks |               |                 |
| 4CI | 0.7                    | 1.88    | 3.5     | 0.153                             | 0.290   | 0.441*  | 0.197         | 0.052           |
|     | 0.69                   | 1.25    | 1.83    | 0.151                             | 0.193   | 0.231   |               |                 |
|     | 0.76                   | 1.13    | 1.14    | 0.166                             | 0.174   | 0.144   |               |                 |
|     | 0.81                   | 1.16    | 2.26    | 0.177                             | 0.179   | 0.285   |               |                 |
| 4FI | 1.03                   | 2.54    | 4.43    | 0.225                             | 0.392   | 0.558   | 0.483         | 0.207           |
|     | 3.37                   | 5.05    | 5.32    | 0.735                             | 0.779   | 0.670   |               |                 |
|     | 1.21                   | 5.43    | 6.43    | 0.264                             | 0.838*  | 0.810*  |               |                 |
|     | 2.85                   | 3.65    | 3.61    | 0.622                             | 0.563   | 0.455   |               |                 |
| 4GI | 5.68                   | 7.99    | 7.62    | 1.239*                            | 1.233*  | 0.960   | 0.908         | 0.181           |
|     | 3.93                   | 6.11    | 6.805   | 0.858                             | 0.943   | 0.857   |               |                 |
|     | 3.79                   | 5.74    | 6.85    | 0.827                             | 0.886   | 0.863   |               |                 |
|     | 4.35                   | 3.57    | 7.19    | 0.949                             | 0.551*  | 0.906   |               |                 |
| 4SI | 1.86                   | 2.69    | 7.11    | 0.406                             | 0.415   | 0.896*  | 0.498         | 0.271           |
|     | 3.47                   | 2.2     | 4.54    | 0.757                             | 0.339   | 0.572   |               |                 |
|     | 5.14                   | 3.92    | 3.55    | 1.122                             | 0.605   | 0.447   |               |                 |
|     | 1.54                   | 1.52    | 2.09    | 0.336                             | 0.235*  | 0.263   |               |                 |
| 5CI | 2.07                   | 2.31    | 1.93    | 0.452*                            | 0.356   | 0.243*  | 0.337         | 0.102           |
|     | 1.72                   | 1.54    | 1.55    | 0.375                             | 0.238   | 0.195*  |               |                 |
|     | -                      | -       | -       | -                                 | -       | -       |               |                 |
|     | 1.66                   | 3.28    | 2.65    | 0.362                             | 0.506*  | 0.334   |               |                 |
| 6CI | 2.51                   | 3.72    | 3.96    | 0.548                             | 0.574   | 0.499   | 0.593         | 0.155           |
|     | 3.39                   | 5.57    | 5.955   | 0.740                             | 0.859*  | 0.750   |               |                 |
|     | 1.66                   | 2.76    | 4.43    | 0.362*                            | 0.426*  | 0.558   |               |                 |
|     | 2.08                   | 3.89    | 6.16    | 0.454                             | 0.600   | 0.776*  |               |                 |

\*Outlying values not included in calculation of average A value

| Mix  | Carbonation Depth (mm) |         |         | Carbonation Coefficient A (mm/√d) |         |         | Ave A<br>(mm/√d) | Std Dev<br>(mm/√d) |
|------|------------------------|---------|---------|-----------------------------------|---------|---------|------------------|--------------------|
|      | 3 weeks                | 6 weeks | 9 weeks | 3 weeks                           | 6 weeks | 9 weeks |                  |                    |
| 4CIP | 0.49                   | 2.4     | 3.99    | 0.107                             | 0.370   | 0.503*  | 0.193            | 0.114              |
|      | 0.29                   | -       | 3.2     | 0.063                             | -       | 0.403   |                  |                    |
|      | -                      | 1.19    | 1.11    | -                                 | 0.184   | 0.140   |                  |                    |
|      | 0.64                   | -       | 4.3     | 0.140                             | -       | 0.542*  |                  |                    |
| 4FIP | -                      | 2.03    | 1.49    | -                                 | 0.313   | 0.188*  | 0.423            | 0.069              |
|      | 1.49                   | 4.57    | 3.38    | 0.325                             | 0.705*  | 0.426   |                  |                    |
|      | 3.73                   | 3.46    | 4.72    | 0.814                             | 0.534   | 0.595   |                  |                    |
|      | 1.82                   | -       | 2.5     | 0.397                             | -       | 0.315   |                  |                    |
| 4GIP | 3.85                   | 4.69    | 6.62    | 0.840                             | 0.724*  | 0.834   | 1.025            | 0.143              |
|      | 6.27                   | 8.18    | 10.72   | 1.368*                            | 1.262   | 1.351*  |                  |                    |
|      | 3.8                    | 4.83    | 9.58    | 0.829                             | 0.745*  | 1.207   |                  |                    |
|      | 6.91                   | 7.74    | 6.12    | 1.508*                            | 1.194   | 0.771   |                  |                    |
| 4SIP | 3.87                   | 4.82    | -       | 0.845*                            | 0.744*  | -       | 0.568            | 0.050              |
|      | 2.34                   | 2.19    | -       | 0.511                             | 0.338*  | -       |                  |                    |
|      | 2.45                   | 4.56    | -       | 0.535                             | 0.704   | -       |                  |                    |
|      | 2.53                   | 3.85    | -       | 0.552                             | 0.594   | -       |                  |                    |
| 5CIP | 1.92                   | 2.53    | 3.5     | 0.419                             | 0.390   | 0.441   | 0.384            | 0.037              |
|      | 2.17                   | 3.72    | 3.65    | 0.474*                            | 0.574*  | 0.460*  |                  |                    |
|      | 2.87                   | 2.19    | 3.08    | 0.626*                            | 0.338   | 0.388   |                  |                    |
|      | 1.55                   | 2.65    | 2.37    | 0.338                             | 0.409   | 0.299*  |                  |                    |
| 4CIX | 0.5                    | 2.34    | 2.54    | 0.109                             | 0.361   | 0.320   | 0.257            | 0.088              |
|      | 0.71                   | 2.31    | 2.52    | 0.155                             | 0.356   | 0.317   |                  |                    |
|      | 1.02                   | 2.15    | 3.83    | 0.223                             | 0.332   | 0.483*  |                  |                    |
|      | 0.8                    | 1.54    | 1.72    | 0.175                             | 0.238   | 0.217   |                  |                    |
| 4FIX | 1.84                   | 2.23    | -       | 0.402                             | 0.344   | -       | 0.383            | 0.034              |
|      | 1.4                    | 3.64    | 3.11    | 0.306                             | 0.562*  | 0.392   |                  |                    |
|      | 2.11                   | 2.77    | 2.34    | 0.460*                            | 0.427   | 0.295*  |                  |                    |
|      | -                      | -       | -       | -                                 | -       | -       |                  |                    |
| 4GIX | 2.95                   | 3.25    | 4.71    | 0.644                             | 0.501*  | 0.593*  | 0.814            | 0.053              |
|      | 3.11                   | 6.04    | 6.65    | 0.679                             | 0.932   | 0.838   |                  |                    |
|      | 3.74                   | 5.96    | 6.72    | 0.816                             | 0.920   | 0.847   |                  |                    |
|      | 4.18                   | 6.2     | 7.96    | 0.912                             | 0.957   | 1.003*  |                  |                    |
| 4SIX | -                      | 1.47    | 1.58    | -                                 | 0.227   | 0.199   | 0.251            | 0.046              |
|      | -                      | 3.2     | 2.76    | -                                 | 0.494*  | 0.348   |                  |                    |
|      | 0.48                   | -       | 1.72    | 0.105                             | -       | 0.217   |                  |                    |
|      | 0.84                   | 2.11    | 2.65    | 0.183                             | 0.326   | 0.334   |                  |                    |
| 5CIX | 0.78                   | 1.51    | 3.265   | 0.170                             | 0.233   | 0.411   | 0.283            | 0.097              |
|      | 0.99                   | 2.46    | 4.16    | 0.216                             | 0.380   | 0.524*  |                  |                    |
|      | 1.27                   | 2.41    | 4.51    | 0.277                             | 0.372   | 0.568*  |                  |                    |
|      | 0.76                   | 2.09    | 1.81    | 0.166                             | 0.322   | 0.228   |                  |                    |

## Appendix I - Bulk Diffusion Results

| Mix | Depth Increments | Ave Depth | Cl <sup>-</sup> content (%) |          |          | Sample 1           |   |                | Sample 2           |   |                | Sample 3           |   |                | Average            |   |                |
|-----|------------------|-----------|-----------------------------|----------|----------|--------------------|---|----------------|--------------------|---|----------------|--------------------|---|----------------|--------------------|---|----------------|
|     | (mm)             | (mm)      | Sample 1                    | Sample 2 | Sample 3 | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> |
| 4CI | 0-4              | 2         | 0.4234                      | 0.3957   | 0.4227   | 0.528              | 2.035E-11   | 0.955          | 0.470              | 1.528E-11   | 0.995          | 0.685              | 1.497E-11   | 0.980          | 0.561              | 1.687E-11   | 0.977          |
|     | 5-8              | 6         | 0.3745                      | 0.2799   | 0.3801   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 9-12             | 10        | 0.2518                      | 0.1497   | 0.2539   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 13-16            | 14        | 0.1030                      | 0.0859   | 0.1056   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 17-20            | 18        | 0.0374                      | 0.0363   | 0.0411   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 21-24            | 22        | 0.0362                      | 0.0331   | 0.0486   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4FI | 0-4              | 2         | 0.4205                      | 0.3692   | 0.3677   | 0.505              | 2.044E-11   | 0.984          | 0.530              | 1.980E-11   | 0.967          | 0.509              | 2.037E-11   | 0.948          | 0.515              | 2.020E-11   | 0.966          |
|     | 5-8              | 6         | 0.3377                      | 0.2102   | 0.2123   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 9-12             | 10        | 0.2289                      | 0.2091   | 0.2025   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 13-16            | 14        | 0.1108                      | 0.1450   | 0.1483   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 17-20            | 18        | 0.0484                      | 0.0528   | 0.0496   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 21-24            | 22        | 0.0381                      | 0.0405   | 0.0406   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4GI | 0-4              | 2         | 0.4997                      | 0.4571   | 0.4567   | 0.249              | 3.535E-11   | 0.977          | 0.557              | 7.589E-12   | 0.960          | 0.579              | 6.214E-12   | 0.974          | 0.461              | 1.639E-11   | 0.970          |
|     | 5-8              | 6         | 0.1800                      | 0.1882   | 0.1772   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 9-12             | 10        | 0.1323                      | 0.1102   | 0.0966   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 13-16            | 14        | 0.0818                      | 0.0556   | 0.0499   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 17-20            | 18        | 0.0696                      | 0.0554   | 0.0407   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 21-24            | 22        | 0.0495                      | 0.0602   | 0.0514   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4SI | 0-4              | 2         | 0.3847                      | 0.4796   | 0.3803   | 0.120              | 4.007E-11   | 0.772          | 0.076              | 8.686E-11   | 0.669          | 0.111              | 5.095E-11   | 0.690          | 0.102              | 5.929E-11   | 0.710          |
|     | 5-8              | 6         | 0.0994                      | 0.0712   | 0.0983   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 9-12             | 10        | 0.0522                      | 0.0446   | 0.0501   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 13-16            | 14        | 0.0384                      | 0.0362   | 0.0411   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 17-20            | 18        | 0.0393                      | 0.0345   | 0.0418   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|     | 21-24            | 22        | 0.0360                      | 0.0385   | 0.0407   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |

| Mix  | Depth Increments | Ave Depth | Cl <sup>-</sup> content (%) |          |          | Sample 1           |   |                | Sample 2           |   |                | Sample 3           |   |                | Average            |   |                |
|------|------------------|-----------|-----------------------------|----------|----------|--------------------|---|----------------|--------------------|---|----------------|--------------------|---|----------------|--------------------|---|----------------|
|      | (mm)             | (mm)      | Sample 1                    | Sample 2 | Sample 3 | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> |
| 4CIX | 0-4              | 2         | 0.8485                      | 0.8409   | 0.8097   | 0.543              | 1.328E-11   | 0.996          | 0.533              | 1.404E-11   | 0.993          | 0.538              | 1.487E-11   | 0.974          | 0.538              | 1.406E-11   | 0.988          |
|      | 5-8              | 6         | 0.3047                      | 0.3052   | 0.3119   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 9-12             | 10        | 0.1782                      | 0.1824   | 0.2016   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 13-16            | 14        | 0.0938                      | 0.0970   | 0.0874   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 17-20            | 18        | 0.0361                      | 0.0391   | 0.0456   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 21-24            | 22        | 0.0317                      | 0.0371   | 0.0543   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4FIX | 0-4              | 2         | 0.6922                      | 0.6901   | 0.6638   | 0.926              | 5.233E-12   | 0.996          | 0.924              | 5.200E-12   | 0.997          | 0.171              | 3.405E-11   | 0.446          | 0.674              | 1.483E-11   | 0.813          |
|      | 5-8              | 6         | 0.3009                      | 0.2994   | 0.1491   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 9-12             | 10        | 0.0916                      | 0.0916   | 0.0496   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 13-16            | 14        | 0.0388                      | 0.0344   | 0.0580   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 17-20            | 18        | 0.0344                      | 0.0365   | 0.0253   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 21-24            | 22        | 0.0396                      | 0.0356   | 0.0751   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4GIX | 0-4              | 2         | 0.5140                      | 0.4422   | 0.5002   | 0.124              | 6.200E-11   | 0.814          | 0.524              | 1.081E-11   | 0.981          | 0.119              | 5.511E-11   | 0.815          | 0.256              | 4.264E-11   | 0.870          |
|      | 5-8              | 6         | 0.1071                      | 0.2185   | 0.0993   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 9-12             | 10        | 0.0701                      | 0.1015   | 0.0690   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 13-16            | 14        | 0.0507                      | 0.0487   | 0.0431   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 17-20            | 18        | 0.0513                      | 0.0542   | 0.0441   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 21-24            | 22        | 0.0478                      |          | 0.0446   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4SIX | 0-4              | 2         | 0.8769                      | 0.7378   | 0.8769   | 0.075              | 1.298E-10   | 0.918          | 0.168              | 2.081E-11   | 0.610          | 0.110              | 6.641E-11   | 0.909          | 0.117              | 7.235E-11   | 0.813          |
|      | 5-8              | 6         | 0.1333                      | 0.1284   | 0.1323   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 9-12             | 10        | 0.0466                      | 0.0343   | 0.0499   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 13-16            | 14        | 0.0504                      | 0.0418   | 0.0607   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 17-20            | 18        | 0.0406                      | 0.0350   | 0.0430   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 21-24            | 22        | 0.0378                      | 0.0411   | 0.0389   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |

| Mix  | Depth Increments | Ave Depth | Cl <sup>-</sup> content (%) |          |          | Sample 1           |   |                | Sample 2           |   |                | Sample 3           |   |                | Average            |   |                |
|------|------------------|-----------|-----------------------------|----------|----------|--------------------|---|----------------|--------------------|---|----------------|--------------------|---|----------------|--------------------|---|----------------|
|      | (mm)             | (mm)      | Sample 1                    | Sample 2 | Sample 3 | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> | C <sub>s</sub> (%) | D <sub>a</sub> x10 <sup>-12</sup> (m <sup>2</sup> /s) | R <sup>2</sup> |
| 4CIP | 0-4              | 2         | 0.5318                      | 0.4348   | 0.5314   | 0.267              | 2.328E-11   | 0.964          | 0.530              | 8.981E-12   | 0.991          | 0.212              | 2.942E-11   | 0.948          | 0.336              | 2.056E-11   | 0.967          |
|      | 5-8              | 6         | 0.1120                      | 0.2252   | 0.1372   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 9-12             | 10        | 0.1167                      | 0.1113   | 0.1166   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 13-16            | 14        | 0.0809                      | 0.0509   | 0.0793   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 17-20            | 18        | 0.0340                      | 0.0379   | 0.0306   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 21-24            | 22        | 0.0307                      | 0.0331   | 0.0303   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4FIP | 0-4              | 2         | 0.3656                      | 0.2943   | 0.3561   | 0.417              | 1.830E-11   | 0.997          | 0.337              | 1.906E-11   | 0.989          | 0.406              | 2.210E-11   | 0.981          | 0.387              | 1.982E-11   | 0.989          |
|      | 5-8              | 6         | 0.2427                      | 0.1968   | 0.2608   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 9-12             | 10        | 0.1580                      | 0.1471   | 0.1549   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 13-16            | 14        | 0.0910                      | 0.0690   | 0.1385   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 17-20            | 18        | 0.0530                      | 0.0352   | 0.0489   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 21-24            | 22        | 0.0366                      | 0.0347   | 0.0324   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4GIP | 0-4              | 2         | 0.3729                      | 0.4086   | 0.3528   | 0.436              | 2.024E-11   | 0.926          | 0.484              | 1.167E-11   | 0.979          | 0.417              | 1.904E-11   | 0.945          | 0.446              | 1.698E-11   | 0.950          |
|      | 5-8              | 6         | 0.3099                      | 0.2427   | 0.2914   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 9-12             | 10        | 0.1321                      | 0.1138   | 0.1245   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 13-16            | 14        | 0.0795                      | 0.0605   | 0.0783   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 17-20            | 18        | 0.1032                      | 0.0553   | 0.0851   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 21-24            | 22        | 0.0501                      | 0.0482   | 0.0394   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
| 4SIP | 0-4              | 2         | 0.6612                      | 0.5471   | 0.6660   | 1.036              | 2.470E-12   | 0.995          | 0.169              | 2.262E-11   | 0.692          | 0.228              | 1.703E-11   | 0.779          | 0.478              | 1.404E-11   | 0.822          |
|      | 5-8              | 6         | 0.1512                      | 0.1271   | 0.1513   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 9-12             | 10        | 0.0482                      | 0.0417   | 0.0509   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 13-16            | 14        | 0.0437                      | 0.0396   | 0.0437   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 17-20            | 18        | 0.0376                      | 0.0381   | 0.0373   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |
|      | 21-24            | 22        | 0.0415                      | 0.0369   | 0.0396   |                    |   |                |                    |   |                |                    |   |                |                    |   |                |

## Appendix J - Concrete Durability Specification Targets (SANRAL)

### Concrete Durability Specification Targets - Carbonation Induced Corrosion

| Design-ation | Description  | Condition of Exposure | Description of Exposure  | Recommended Minimum Cover (mm) | In-situ Durability Index for various Cover Depths within Exposure Condition - 100 Year Life |                   |               |                   |               |      |
|--------------|--|-----------------------|--|--------------------------------|---|-------------------|---------------|-------------------|---------------|------|
|              |  |                       |  |                                | Cover Depth (mm)  | OPI (log scale)   |               | Sorptivity (mm/h) |               |      |
|              |  |                       |  |                                |   | Recommended value | Minimum value | Recommended value | Maximum value |      |
| XC1a         | Low hum. (<50%); exter. conc. sheltered from moisture, arid areas; interior concrete | Mild                  | Inland dry areas - arid to semi-arid, Karoo etc. Very low (<40%) to low humidity (40% - 50 %). Concrete surfaces not in contact with ground, protected against wetting.  | 40                             | 40 mm min. cover  | N/A               | N/A           | 10.0              | 12.0          |      |
| XC1b         | Permanently wet or damp  |                       | All areas with access to external or environmental moisture Saturated conditions (RH >95%). Concrete surfaces above ground level kept permanently moist by exposure to water; concrete that never appreciably dries. Concrete surfaces below ground such as piles and buried foundations or abutments kept permanently damp. | 40                             | 40  | 9.20              | 9.00          | 10.0              | 12.0          |      |
|              |  |                       |  |                                | 50  | 9.00              | 9.00          | 10.0              | 12.0          |      |
|              |  |                       |  |                                | 60  | n/a               | n/a           | n/a               | n/a           |      |
| XC2          | Wet, rarely dry  | Moderate              | All areas with access to external or environmental moisture Concrete surfaces above ground level kept mostly in moist condition by exposure to water; concrete may occasionally dry for appreciable periods such as when tanks are emptied   | 40                             | 40  | 9.40              | 9.00          | 10.0              | 12.0          |      |
|              |  |                       |  |                                |   | 50                | 9.10          | 9.00              | 10.0          | 12.0 |
|              |  |                       |  |                                |   | 60*               | 9.00          | 9.00              | 10.0          | 12.0 |
|              |  |                       |  |                                |   | 70*               | n/a           | n/a               | n/a           | n/a  |
| XC3          | Moderate Hum. (50-80%). Ext. conc. sheltered from rain in non-arid areas             |                       | Near-coastal areas with no chlorides; moist inland areas; adjacent to dams, lakes, major rivers Moderate humidity (50% to 80%), moist climate. Exterior concrete surfaces in moist areas or adjacent to major water bodies, permanently sheltered from rain or direct surface moisture                                       | 40                             | 40  | 9.40              | 9.00          | 10.0              | 11.0          |      |
|              |  |                       |  |                                | 50  | 9.10              | 9.00          | 10.0              | 11.0          |      |
|              |  |                       |  |                                | 60*   | 9.00              | 9.00          | 10.0              | 11.0          |      |
|              |  |                       |  |                                | 70*   | n/a               | n/a           | n/a               | n/a           |      |
| XC4          | Cyclic wet and dry   | Severe                | All areas with access to external or environmental moisture; arid areas excluded Moderate humidity (50% to 80%), moist climate. Concrete surfaces exposed to rain or alternately wet and dry conditions  | 45                             | 40  | 9.60              | 9.20          | 10.0              | 10.0          |      |
|              |  |                       |  |                                | 50  | 9.30              | 9.00          | 10.0              | 10.0          |      |
|              |  |                       |  |                                | 60*   | 9.10              | 9.00          | 10.0              | 10.0          |      |
|              |  |                       |  |                                | 70*   | 9.00              | 9.00          | 10.0              | 10.0          |      |

WARNING: Covers shown with an asterisk (\*) should be avoided so as to (i) limit crack widths, and (ii) ensure durability concrete is being specified and must be discussed with the client before being specified.

NOTE: Heavily Polluted Industrial Areas : Increase Cover for any exposure Condition above by 10mm

*Concrete Durability Specification Targets - Chloride Induced Corrosion*

| Designation | Description  | Condition of Exposure | Description of Exposure   | Recommended Minimum Cover (mm) | In-situ Durability Index for various Cover Depths within Exposure Condition - 100 Year Life |                               |                 |                 |                  |                   |               |
|-------------|--|-----------------------|---|--------------------------------|---|-------------------------------|-----------------|-----------------|------------------|-------------------|---------------|
|             |  |                       |   |                                | Cover Depth (mm)  | Chloride Conductivity (mS/cm) |                 |                 |                  | Sorptivity (mm/h) |               |
|             |  |                       |   |                                |   | Typical Binder Blends         |                 |                 |                  |                   |               |
|             |  |                       |   |                                |   | 70:30 CEM1:FA                 | 50:50 CEM1:GGBS | 50:50 CEM1:GGCS | 90:10 CEM1 : CSF | Recommended value | Maximum value |
| XS1         | Exposed to airborne salt but not in direct contact with seawater or inland saline waters | Very Severe           | Proven presence of chlorides; generally < 1km from sea, and coastal river valleys (where chlorides are present) and estuaries, or the presence of chlorides proven by experience or testing. This will include inland salt pans or groundwater carrying slats, etc  | 50                             | 40  | 1.50                          | 1.60            | 2.10            | 0.40             | 10.0              | 12.0          |
|             |  |                       |   |                                | 50  | 2.10                          | 2.20            | 2.80            | 0.50             | 10.0              | 12.0          |
|             |  |                       |   |                                | 60  | 2.60                          | 2.70            | 3.40            | 0.65             | 10.0              | 12.0          |
| XS2a        | Permanently submerged in sea (or saline waters)  | Severe                | Permanently (or substantially) submerged: in the sea (without heavy wave action); in coastal saline estuaries & rivers; in any aggressive saline waters Concrete surfaces exposed to heavily polluted industrial waters; permanently or substantially submerged or permanently wet saline conditions (Generally oxygen starved area approximately 1-1.5m below spring tide level) | 50                             | 40  | 1.00                          | 1.10            | 1.40            | 0.30             | 10.0              | 11.0          |
|             |  |                       |   |                                | 60  | 1.40                          | 1.60            | 2.00            | 0.40             | 10.0              | 11.0          |
|             |  |                       |   |                                | 60  | 1.80                          | 2.10            | 2.50            | 0.50             | 10.0              | 11.0          |
| XS2b        | XS2a + exposed to abrasion   | Extreme               | As above, but with heavy wave action; in any aggressive saline waters where abrasion occurs   | 60 (Mandatory)                 | 60  | 1.45                          | 1.70            | 2.00            | 0.40             | 10.0              | 11.0          |
| XS3a        | Tidal, splash & spray zones  | Extreme               | Sea or saline estuaries and rivers, but not permanently submerged; tidal zone; and in a spray or splash zone. surfaces exposed to aggressive saline waters, including heavily polluted industrial waters, without being permanently wet.  | 50                             | 40  | 0.65                          | 0.85            | 1.00            | 0.25             | 10.0              | 10.0          |
|             |  |                       |   |                                | 50  | 1.10                          | 1.35            | 1.45            | 0.35             | 10.0              | 10.0          |
|             |  |                       |   |                                | 60  | 1.45                          | 1.70            | 2.00            | 0.40             | 10.0              | 10.0          |
| XS3b        | XS3a + exposed to abrasion   |                       | As above, but with heavy wave action or where abrasion or erosion can occur   | 60 (Mandatory)                 | 60  | 1.10                          | 1.30            | 1.55            | 0.30             | 10.0              | 10.0          |

University of Cape Town