UNIVERSITY OF CAPE TOWN

CONCRETE MATERIALS & STRUCTURAL INTEGRITY RESEARCH UNIT

DEPARTMENT OF CIVIL ENGINEERING

THE INTEGRATION OF NON-DESTRUCTIVE TEST METHODS INTO THE SOUTH AFRICAN DURABILITY INDEX APPROACH

Presented by,

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March 2013

DECLARATION

I declare that this dissertation is my own work. I have not plagiarised, nor tried to pass another authors work as my own. I have made every effort to ensure that where literature, discussions, collaboration, or contributions from other authors have been made, that it has been clearly acknowledged. This work has not been submitted previously at any other institution for any degree. This thesis is in submission of partial requirements for the degree of Master of Science in Engineering at the University of Cape Town.

Signed by candidate

Simon Starck

March 2013

ACKNOWLEDGEMENTS

I would like to thank the following people for their assistance during my thesis, as well as throughout my postgraduate degree:

- Associate Prof. Hans-Dieter Beushausen, my thesis supervisor, for your assistance throughout the duration of this thesis. Thank you for the experiences which you provided, and for always being available and willing to help.
- Prof. Mark Alexander, thank you for your help with this research and your knowledgeable guidance.
- Mike Otieno, thank you for your continuous support and assistance with my thesis, and for the many hours which you have spent helping me improve my work.
- Dr. Roberto Torrent, thank you for many discussions and assistance which you have generously provided, for much valuable insight and many creative ideas to aid this thesis.
- Nooredien Hassen, a special thanks for all the support you have given to aid this research. Also to Charles May, Elvino Witbooi, Hector Mafungwa, Leonard Adams and Danovan Ferus for all your help in the laboratories.
- Special thanks to M. Romer and A. Leemann for providing experimental data and other information aiding this thesis.
- To the Concrete Materials & Structural Integrity Research Unit (CoMSIRU), for ongoing support through my academics.
- To my friends with whom I have spent the two years, for your encouragement and support. A special thanks to Matteo Angelucci, Janina Kanjee, Kyle Wickins and Ben Walker for the camaraderie. Without you this experience would have not been the same.
- To my family, Gran, Mom, Dad and Brother for supporting my throughout my studies. Also, to my grandparents who were not able to see me bring this to completion, I dedicate this to you.

My Lord and Saviour, Jesus Christ, for

blessing me abundantly, always.

ABSTRACT

In past years, the durability of many reinforced concrete (RC) structures has been found to be inadequate. This has resulted in costly repair and rehabilitation, to ensure the expected design service life is achieved. For this reason, much research has been directed towards improving the durability of RC structures, and methods for monitoring durability performance.

In South Africa, the Durability Index (DI) approach is a performance-based method for specifying (or assessing) the durability of RC structures. The oxygen permeability index (OPI) test is being standardised in South Africa, and has been implemented in a large scale project by the South African National Roads Agency Limited (SANRAL). However, the semi-invasive nature of the test method (due to core extraction) has been seen as undesirable by engineers and clients. The Swiss approach (after Swiss Standard SIA 262/1) is another performance-based approach, which makes use of an air-permeability test method (the Torrent method) for specifying or assessing the durability of RC structures. Until recently, there has been a considerable amount of uncertainty linked to the influence of moisture content on the Torrent permeability coefficient. This study aims to incorporate the Swiss approach into the DI approach, in order to achieve a non-destructive, nationally accepted approach for comprehensive durability assessment of RC structures.

Previous studies by the RILEM Technical Committee 189-NEC (2005), EMPA (2006) and Wieland (2009) provide support for further investigation into an integrated approach of this type. The experimental programme included the design of six concrete mixes, using two cement types (100% PC CEM I 52.5N and 50/50% PC/GGBS), three w/c ratios (0.50, 0.65, 0.80), two compaction methods, two simulated natural environments (typical summer and winter exposure in Cape Town), and three testing ages (35, 40 and 90 days). Cubes (150 mm) were prepared, and tested using both the OPI test (in accordance with the DI approach) and Torrent method (in accordance with current recommendation for the Swiss approach). The surface moisture content at testing was also investigated, in order to provide quantification of the effect of moisture content on the Torrent method.

The OPI test and Torrent method were shown to be sensitive to common intrinsic and extrinsic concrete properties. These included w/c ratio, cement type and environmental exposure. The moisture measurement techniques (as presented in the Swiss approach) were found adequate in order to minimise the 'pore blocking' effect of moisture on concrete permeability. The general equation describing the correlation was well approximated by a power function ($R^2 = 0.948$), also confirming the general trend found in previous studies. Three alternatives for practical implementation of the integrated approach were developed. The alternatives for full implementation include the option to (i) account for, or (ii) neglect, the effect of moisture on the Torrent measurement. Further, potential for partial implementation is presented in order to perform a more comprehensive durability assessment. Through implementation of the integrated approach, opportunities for verification and refinement of the correlation (on which the approach is based) are possible. The approach presents a forward thinking means for durability assessment of RC structures in South Africa.

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LIST OF SYMBOLS AND ACRONYMS

The following acronyms were used:

CC:	Chloride conductivity (mS/cm)
CSF:	Condensed silica fume
DI:	Durability Index
FA:	Fly ash
GGBS:	Ground granulated blastfurnace slag
ITZ:	Interfacial transition zone
NDT:	Non-destructive test
OPC:	Ordinary Portland cement (usually specified where no extenders are used in the mix design)
OPI:	Oxygen permeability index (log)
PC:	Portland cement
P-TORR:	"PermeaTORR" manufactured by Materials Advanced Services SRL.
RC:	Reinforced concrete
SA:	South Africa
Sorp:	Water sorptivity (mm/h$^{0.5}$)
TPT:	"Torrent Permeability Tester" manufactured by PROCEQ

The following symbols were used:

k_T:	Gas-permeability coefficient (m^2) for the Torrent method
k_{Ts}:	Maximum limiting k_T - value in accordance with SIA 118/262
k_{Ti}:	Maximum limiting k_T - value in accordance with Jacobs (2009)
$k_{Ti\,geomean}$:	Geometric mean k_T - value from experimental work
k_{OPI} :	k-value obtained from OPI test (m/s)
$k_{OPI\ arimean}$:	Arithmetic mean k_{OPI} - value from experimental work
w/c:	Water to cement ratio
ρ:	Resistivity (kΩ.cm)

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CHAPTER 1

1 INTRODUCTION

1.1 Subject

This study aims at investigating the potential for integration of non-destructive test (NDT) methods in the South African Durability Index (DI) approach. In particular, this integration is based on the fundamental relationship between two permeability-related test methods, namely the oxygen permeability index (OPI) test and the Torrent method. The study aims to develop an empirical basis for integration of these methods. The primary benefits of incorporating the Torrent method into the DI approach would include the possibility for a non-destructive, nationally accepted approach for durability assessment. Further, a more comprehensive durability assessment (by taking more measurements) would also be possible, and hence the possibility for development of improved guidelines for durability-based conformity control.

This study presents the basis for an integrated approach, and opportunities for expansion of the DI approach to incorporate the Torrent method. This could result in a number of benefits for performance-based durability design and assessment in South Africa.

1.2 Background

In past years, the durability of many reinforced concrete (RC) structures has been found to be inadequate. For this reason many undergo premature deterioration (Alexander et al., 2008). Poor durability often results in expensive repair and rehabilitation, which could have been prevented by improved durability-based design and construction quality. For this reason, much research has been directed towards improving the durability of RC structures and methods for monitoring durability performance.

A durable RC structure is considered to be one which will remain serviceable and safe for its intended design service life, with minimal repairs and rehabilitation (Ballim et al., 2009). The performance of a RC structure, for durability purposes, is largely measured by the rate of deterioration of the structure. Specifically, durability is commonly measured by the severity of deterioration which affects (or contributes towards) reinforcement (or rebar) corrosion. Figure 1.1 shows the effect of design, construction and durability for a given RC structure over its intended design service life.

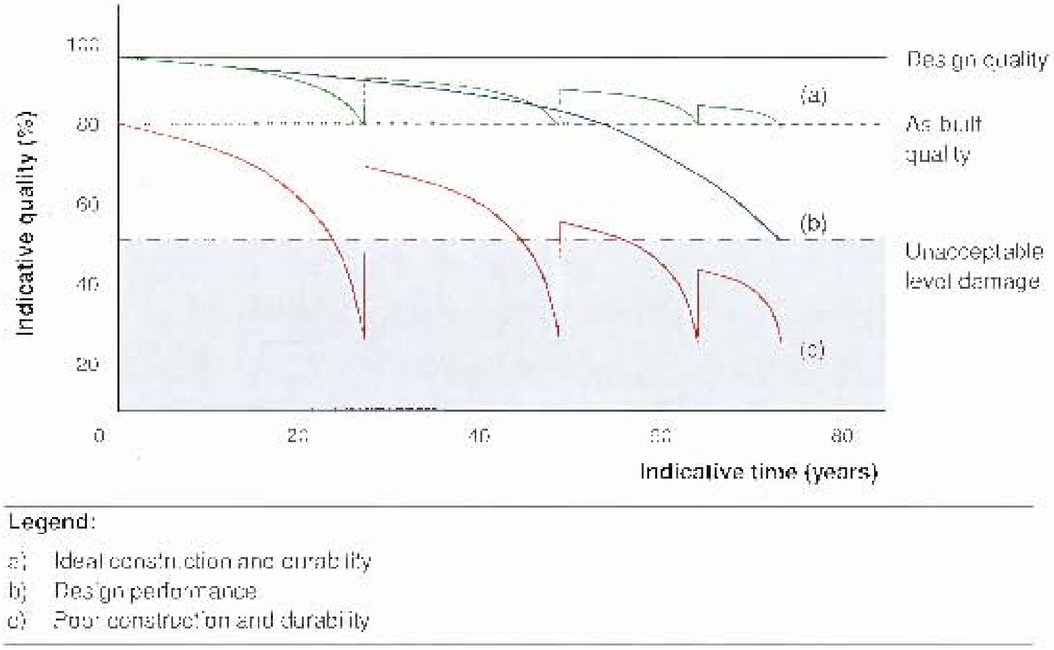


Figure 1.1: Deterioration and rehabilitation of reinforced concrete structures Adapted from Ballim et al. (2009)

As shown in Figure 1.1, an initial loss of quality may occur as a result of poor construction practice. This loss, commonly attributed to defects such as poor compaction and insufficient curing, are represented by the difference in the design and as-built qualities. The design quality is shown decreasing with negligible construction defects, reaching an unacceptable level of damage only at the specified the design service life age. However, the real deterioration of a RC structure may be more likely to lie in the envelope created between ideal construction and durability and poor construction and durability performance curves.

An ideal RC structure assumes negligible losses in quality due to poor construction practice. Further, since greater emphasis is placed on the durability of the structure, the rate at which deterioration occurs is slow, and hence the structure requires minimal rehabilitation and maintenance during operation. It should be noted that the quality of an ideal RC structure also never reaches a critical level (at which safety may become a concern). A poor RC structure is assumed to have maximum losses in quality as a result of poor design or construction, further, since the structure has not been designed for durability, high rates of deterioration are experienced with high maintenance and rehabilitation-related costs. In this case, the safety of the structure may also become questionable. Figure 1.1 also suggests that if monitoring and repair/rehabilitation is performed more frequently, the quality of the structure is expected to remain higher throughout its design service life.

As described, the durability of a structure is dependent on design, construction, and methods of monitoring employed. Monitoring allows early detection of poor concrete quality and construction defects, and hence provides an opportunity to perform early maintenance and rehabilitation. Durability monitoring at early ages (using performance assessment methods), also provides an opportunity for consulting engineers to penalise poor workmanship, and hence provides incentive for good quality work by contractors.

This study will focus primarily on possible improvements to the DI approach, which is used to monitor and assess the durability of RC structures in South Africa. More specifically, this work investigates deterioration of RC structures due to carbonation-induced steel corrosion (viz. for structures exposed to carbon dioxide (CO_2) and moisture). Carbonation is a diffusion process, which results in the lowering of the concrete pore water pH from approximately 12.5 to 8.5. If this process occurs near to the reinforcing steel, in the presence of oxygen and moisture, depassivation and thereafter corrosion of the reinforcing steel will occur (Richardson, 2002; Ballim et al., 2009). Carbonation moves through the concrete as a 'front', at a rate which is controlled by the carbon dioxide concentration at the surface, intrinsic concrete properties, as well as the moisture and oxygen (O_2) content available. This front moves from the concrete surface through the covercrete (layer between open surface and reinforcing steel) into the bulk concrete (Ballim et al., 2009).

An important intrinsic property of the covercrete, which represents the rate at which the carbonation 'front' moves, is permeability. Permeability is commonly defined as the ease with which fluids are able to pass through a particular material under an applied pressure gradient. Fluids in this case include gases such as air, O_2 and CO_2, and liquids such as water (H_20). Factors affecting the rate of carbonation may be classified as either intrinsic or extrinsic concrete properties (Romer, 2005). Intrinsic properties consist of mix design properties such as w/c ratio, aggregate size and type, water content and cement content. Extrinsic factors (viz. construction quality) account for the competence of on-site practice such as reinforcement specification and detailing (which directly affects the covercrete thickness), mixing, pouring, compaction and curing. Construction quality should also account for construction defects, such as cracking and honeycombing, as these provide a direct path from the environment (through the covercrete) to the surface of the reinforcing steel. Much literature is available highlighting the importance of durability and its dependence on covercrete properties (Romer, 2005; Alexander et al., 2008; Torrent and Jacobs, 2009).

In order to predict and monitor the expected design service life of a RC structure, a number of approaches have been developed. In the past, these approaches relied on prescriptive ('recipe-like') specifications for intrinsic concrete properties such as w/c ratio, minimum cement content, and compressive strength for a given environment (Ballim et al., 2009). It has been argued that these prescriptive approaches are not adequate for ensuring durability, as they ignore the performance of different cement types (primary cement and cement extender), as well as extrinsic influences such as construction quality (Ballim et al., 2009). On the basis of this, permeability-related performance-based methods for RC structures in environments exposed to carbon dioxide have been developed. Of particular interest for this study are the oxygen permeability index (OPI) test (from the DI approach) and the Torrent method (performed in accordance with Swiss Standard SIA 262/1:2003).

The South African DI approach can be used to aid design and also assess (or verify) the quality of new concrete structures (Alexander et al., 2008). The approach is in the process of being standardised in South Africa (based on carbonation depth), and is to be included into the South African national standards (SANS). However, the DI approach has been met with some resistance, primarily due to the semi invasive nature of the test (for each test, core extraction is required from the structure). In order to satisfy the concerns of clients and engineers, "mock-up" panels were recommended. "Mock-up" panels are cast in-situ, from the 'same' concrete, and under 'identical' preparatory conditions as the real structure. In South Africa, they commonly have the dimensions 600 x 400 x 150 mm. In theory, these panels should be almost identical to the real structure, however, there is good reason for special attention to be paid to these panels by contractors, especially if meeting the limiting DI requirements is enforced directly by means of a contractual penalty system. These panels also require special formwork for construction, and removal from site after the DI test cores have been extracted. The last possibility for use of the DI approach for conformity (or verification) is to cast laboratory samples from the same mix design, and cure in same manner as specified on-site. However, the true representative nature of these cubes may be questionable (Bentur and Mitchell, 2008). In summary, the DI approach (and in particular the OPI test) is in the process of being standardised, however, the semi-invasive nature of the test (due to core extraction) has been seen as undesirable by engineers and clients.

Non-destructive test (NDT) methods are becoming well accepted for in-situ testing of RC structures. In particular, these are often used for an assessment of durability-related properties. According to the Swiss Standard SIA 262/1 (2003), an air-permeability test method (e.g. the Torrent method) may be used for performance-based durability specification. However, no limiting values or conformity criteria were presented. A project was funded by the Swiss Federal Bureau of Roads (ASTRA) to prepare a comprehensive recommendation for use of the Torrent method in accordance with the Swiss Standard SIA 262/1. These findings were presented in VSS report 641 by Jacobs et al., (2009). It is expected that the current recommendations (largely as a result of the VSS report 641 findings) will be included in the Swiss Standard for 2013 (Torrent et al., 2012).

The Torrent method is performed using a portable, completely non destructive instrument. The advantage of the method is that the real structure can be tested, and due to its non-destructive nature, a greater number of test measurements are possible resulting in a more comprehensive assessment of the structure. The shortfall of this method is that the effect of moisture on the test method is not completely understood. For this reason the interpretation of the results is not conclusive. In summary, the Torrent method has the advantage of being a purely NDT method (meaning the structure itself may be comprehensively assessed, with no damage to the structure), however, the influence of moisture makes the interpretation of the results inconclusive.

The OPI test and Torrent method are both performance-based, permeability-related, test methods for assessing the durability of structures in an environment with exposure to carbon dioxide and moisture. The advantages and disadvantages of each method have been outlined, and on this basis an integrated approach is proposed. The integrated approach relies on the relationship between these two tests methods, and presents an approach which is essentially non-destructive, while still founded on a standardised approach. This presents the possibility for a completely non-destructive performance-based test method in South Africa, and creates the opportunity for a more comprehensive durability assessment of RC structures. The benefits of such an integrated approach also include greater support for the Torrent method through the OPI test, specifically with regards to the influence of moisture on the test method.

1.3 Research significance

Performance based test methods, such as the South African DI approach and Torrent method, are becoming increasingly accepted as a means of verification and assessment of the durability of RC structures. The DI approach has been adopted into large scale construction projects by the South African National Roads Agency Limited (SANRAL), and is soon to be incorporated into the South African national standards. However, the semi-invasive nature of the test causes engineers and clients to have reservation about the use of the approach. The true representative nature of using "mock-up" panels and laboratory samples has also been deemed inconclusive. For this reason, the approach would benefit from the complimentary use of the Torrent method, provided the OPI test was used as the standardised basis for analysis. The Torrent method (supplementary to the OPI test) would create opportunity for a more comprehensive study of the structure, which would allow conclusions regarding conformity to be drawn. The influence of moisture on the Torrent method has not yet been fully understood, hence, the Torrent method would benefit from further studies which reinforce the service life prediction model currently being proposed, and additionally, a qualitative comparison of the effect of moisture on the test method.

In addition to the benefits of an integrated approach for these two performance-based test methods, the successful fulfilment of the integrated approach may provide a quick, easy and standardised method for comprehensive durability assessment of RC structures. An integrated approach may also provide insight into the conformity of construction work. The study also serves to illustrate the close link between the two test methods, and hence promote further acceptance of the methods by engineering firms in South Africa and abroad.

1.4 Hypothesis

A correlation exists between the oxygen permeability index (OPI) test and Torrent method, and this correlation can be modelled (with acceptable statistical significance) for various concrete types and environmental conditions.

Air-permeability testing, using the Torrent method, can therefore be used in conjunction with the standardised oxygen permeability index (OPI) test (in the South African Durability Index approach), in order to provide a conclusive non-destructive measure of the permeability of the covercrete, and hence provide insight into the service life and durability of a reinforced concrete structure.

1.5 Research objectives

The objectives of this research are to:

- Investigate the effect of intrinsic factors (w/c ratio, binder type) and extrinsic factors (curing, compaction) on the oxygen permeability index (OPI) test and Torrent method.
- Establish a correlation between two permeability-based tests methods, namely, the oxygen permeability index and Torrent method.
- Evaluate the correlation fundamentally, as well as based on experimental test results for various concrete types and environmental conditions.
- Present the opportunity for improvement of the South African Durability Index approach to include the supplementary use of Torrent method. In addition, present the limitations of the use of the Torrent method for this application.
- Present the basis for an integrated approach, as well as the advantages (and limitations) of this approach.

1.6 Scope of study

The scope of this study is limited to the following aspects:

- Two performance-based durability test methods, which measure the fluid permeability of the covercrete, namely the oxygen permeability index (OPI) test and Torrent method, were selected.
- The study is limited to RC structures being investigated for deterioration, where the primary deterioration mechanism for reinforcement corrosion is carbonation. The effects of physical attack (viz. by erosion, frost attack or extreme temperatures) are not considered. If chlorides are also to be considered, another approach for durability assessment should be considered.
- This investigation is aimed at new structures for the assessment (or evaluation) of the covercrete properties. The outcome may also be useful for service life prediction of the RC structure, and enforcing penalties for unsatisfactory construction work.

- Purely Portland cement (PC) concretes are becoming less common with advances in supplementary cement extenders. Common extenders used in South Africa are ground granulated blastfurnace slag (GGBS), fly ash (FA) and condensed silica fume (CSF). Extenders provide a number of advantages for improving durability and reducing costs. In this study, a plain Portland cement mix (100% PC) and a ground granulated blastfurnace slag blend (50/50% GGBS/PC) were selected. The PC mix was selected to represent a control mix, while the GGBS/PC mix was selected to investigate the influence of a common extender on the test methods.
- Common w/c ratios for ensuring durable structures vary between 0.40 and 0.60. Three w/c ratios were selected for this study, specifically w/c ratios of 0.50, 0.65 and 0.80. These were possibly higher than expected for RC structures designed for durability, however, it was important to ensure that the upper limit for durability requirement (for both test methods) was achieved (and exceeded). This will be explained further in Chapter 3.
- In order to best simulate the real life of RC structures, two types of curing, compaction and concrete age were specified. Curing methods were simulated for summer and winter environments, compaction was simulated for well vibrated and poorly vibrated concrete, and testing was performed at approximately 35 and 90 days after casting. A number of problems were encountered relating to specification of the degree of compaction. More information regarding these methods is presented in Chapter 3.

1.7 Plan of development

This thesis will be presented in the following sections:

Chapter 1 provides a general overview of of the topic, and gives background to the field of study. The hypothesis is presented, as well objectives of the research and the scope and limitations.

Chapter 2 presents a synthesis of available literature providing a basis for the work to follow. The transport mechanisms commonly found in concrete are discussed, drawing special attention to permeability in concrete. Thereafter the deterioration of RC structures, as well as current service life prediction models are outlined. Factors affecting the permeability of concrete are then identified, followed by available permeability-based measurement techniques. The South African Durability Index approach and Torrent method, two performance-based approaches, are then described, paying special attention to the respecive measurement techniques presented earlier. Finally, previous studies which support an integration of this type are summarised, and thereafter a short summary of the literature presented.

Chapter 3 outlines the experimental programme used to achieve the thesis objectives. The procedure for sample preparation and preconditioning is described, and thereafter the method for testing and data collection explained.

Chapter 4 provides an analysis of experimental results using both the OPI test (from the DI approach) and the Torrent method. Thereafter, the results are compared and discussed, in order to evaluate the correlation developed.

Chapter 5 provides an overview of the proposed integrated method, and discusses a possible implementation strategy for the approach. The limitations of the method are also outlined.

Chapter 6 provides closure to this thesis, as well as recommendations for further work. A critical evaluation of the integrated approach is provided.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

2.1.1 Overview

This chapter begins by describing the fundamental transport mechanisms in concrete, with the focus being on that of permeation. Thereafter, the deterioration processes of concrete are presented, with emphasis on deterioration to RC structures caused by carbonation-induced steel corrosion, and the effect of carbonation on service life prediction of RC structures. The available methods for permeability-based measurement (both laboratory-based and on-site) are then discussed, with the oxygen permeability index (OPI) test and Torrent methods being presented in much detail. Two performance-based standards (or recommendations), namely, the South African Durability Index (DI) approach and Swiss Standard SIA 262/1, are then described. This is followed by a review of existing research which supports an integrated approach, based on permeability measurements on RC structures.

2.1.2 Objectives and focus areas

The objectives of this chapter may be summarised as follows:

- Describe the fundamental transport mechanisms in concrete, in particular, that of permeation, which has been linked to the rate of carbonation.
- Present the common deterioration processes for RC structures, and the relationship between permeation, carbonation and the methods used for service life prediction of RC structures in environments where carbonation-induced steel corrosion is the primary deterioration mechanism.
- Discuss the factors which affect the permeability of concrete, by considering both intrinsic and extrinsic (dependent on the quality of construction practice) concrete properties.
- Present available methods for measurement of the permeability of concrete, clearly distinguishing between the methods, as well as providing an overview of their advantages and disadvantages.
- Provide an overview of common performance-based approaches for the durability assessment (and specification) of RC structures, linking this to the respective permeability-based measurement techniques.

- Present previous studies, whose results support the further investigation into a permeability-based integration of the two performance based standards (or recommendations), namely, the South African Durability Index (DI) approach and Swiss Standard SIA 262/1.

2.2 Transport mechanisms in concrete

Transport mechanisms in concrete describe the mechanisms by which the movement of ions or molecules under specific processes is possible (Richardson, 2002). In the past, the governing transport mechanisms have been investigated in order to describe and explain the degradation phenomena found in concrete structures (Kropp and Alexander, 2007). These degradation phenomena can then be used to describe durability (Kollek, 1989; Ballim et al., 2009). The service life of a RC structure can be estimated based on these durability related transport mechanisms. Common deterioration mechanisms include the processes for chloride ingress (due to marine exposure), carbonation (due to carbon dioxide exposure) and various other forms of chemical attack (such as sulphate attack) (Torrent et al., 2007; Ballim et al., 2009).

The protection of a RC structural member against aggressive species is governed by the penetrability and thickness of the surface layer of concrete (typically 10-50mm) between the exposed concrete face and rebar (Kollek, 1989; Dinku and Reinhardt, 1997; Kropp and Alexander, 2007; Torrent et al., 2007). This layer is commonly referred to as the covercrete (abbreviating 'cover concrete'), and is usually described by means of transport mechanisms (such as permeability) and thickness. Molecular or ionic movement may occur as a result of capillary action, flow under pressure, flow under an electrical field, or flow under a concentration gradient (Ballim et al., 2009). Common transport mechanisms in concrete include convection; diffusion; migration (or conduction); permeation; permittivity; absorption and wick action (Hilsdorf, 1995; Puyate and Lawrence, 2000; Claisse, 2005; Ballim et al., 2009). Since the focus of this thesis is on durability assessment, only transport mechanisms most closely linked to deterioration phenomena (and hence the deterioration of concrete) will be described in detail. These include diffusion, sorptivity, migration (or conduction) and permeation.

2.2.1 Pore structure and the hydration process

Concrete commonly consists of coarse aggregate, fine aggregate (sand), water, cement (and cement extenders) and admixtures. In its fresh state, the cement paste consists of evenly dispersed unhydrated cement grains suspended in water (Grieve, 2009). The hydration and cementing reactions (and governing factors thereof) of Portland cement (PC), ground granulated blastfurnace slag (GGBS), fly ash (FA) and condensed silica fume (CSF) cement extenders are well documented in the literature by Neville (1981); Grieve (2009); and Alexander and Beushausen (2011) and therefore will not be described in detail. However, the pore structure of the concrete in its hardened state, directly influences the penetrability of concrete, and hence is of great importance for durability assessment.

In its hardened state, the cement paste incorporates two types of pores, namely gel and capillary pores. Gel pores are caused by the formation of calcium silicate hydrate (e.g. $3CaO.2SiO_2.3H_2O$) in the hydration process, due to small interstitial spaces between linked fibres. The hydration process, and subsequent porosity of the capillary and gel voids is explained by the Power's model for hydration (Powers and Brownyard, 1947), which describes the cement paste in terms of unreacted cement, free water (which links to capillary porosity) and hydration product (which links to gel porosity) (Powers and Brownyard, 1947). The gel pores constitute approximately 28% of the total gel volume (Neville, 1981) after drying the concrete in a standard manner such as that of Copeland and Hayes (1953). The water present inside the gel pores becomes physically bonded, and is only evaporable at above 105°C (Neville, 1981).

The capillary pores (dependent on w/c ratio, degree of hydration and cement type) are significantly larger. They exist as free volume, where hydration product has not been able to occupy volume originally filled with mix water in the fresh state (Richardson, 2002). Hydrated grains occupy approximately twice the volume of unhydrated cement grains, and hence to reduce the total porosity of the cement paste, it is critical that as much of the capillary pore volume is removed as possible (Richardson, 2002). The water content of the capillary pores may vary, and is evaporable below 105°C (Neville, 1981). Figure 2.1 shows the general pore structure for hydrated cement paste.

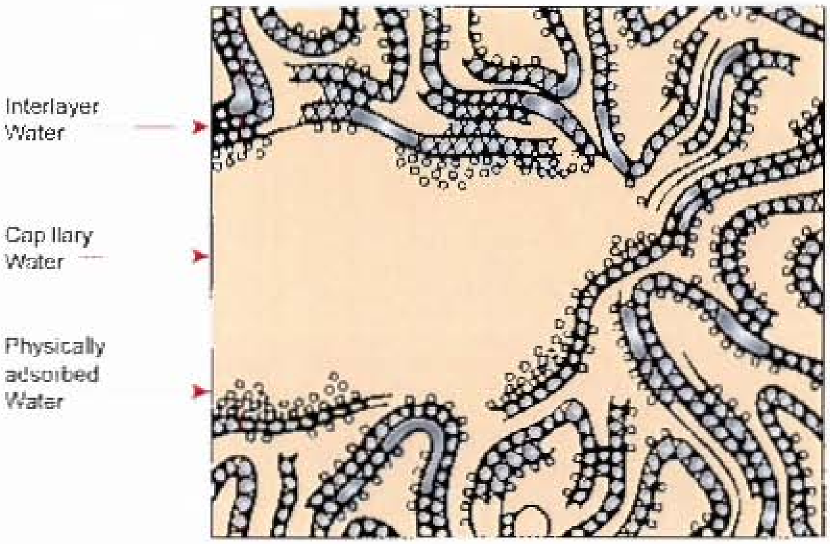


Figure 2.1: Pore structure of hardened cement paste (Mehta and Monteiro, 2006)

2.2.2 Penetrability and percolation

Penetrability is a term used to describe the degree to which a material allows the transport of ions or molecules. Penetrability of concrete may be described by one or more transport mechanisms, for example permeation, sorption, conduction and diffusion (Hilsdorf, 1995; Alexander and Mindess, 2005). On the other hand, percolation describes whether a material is penetrable or not (Alexander and Mindess, 2005). The concept of percolation tries to explain connectivity in the matrix, or more specifically, the point at which complete pore connectivity is established in a given space (Garboczi, 1995).

Hardened concrete may be considered a three-phase material, consisting of solids (aggregate and cement paste), air and water (Richardson, 2002). The processes of penetrability will commonly choose the path of least resistance when penetrating the concrete matrix. Due to the structure of concrete, three quite different regions of penetrability (governed by different factors) are recognised. These regions may be grouped as follows:

- Coarse aggregate
- Interfacial transition zone (ITZ)
- Cement paste matrix

Each of these materials (or regions) has their own unique transport properties (Ballim et al., 2009). Figure 2.2 shows the typical concrete microstructure at the aggregate-paste interface. In particular, the ITZ links the aggregate and bulk cement paste.

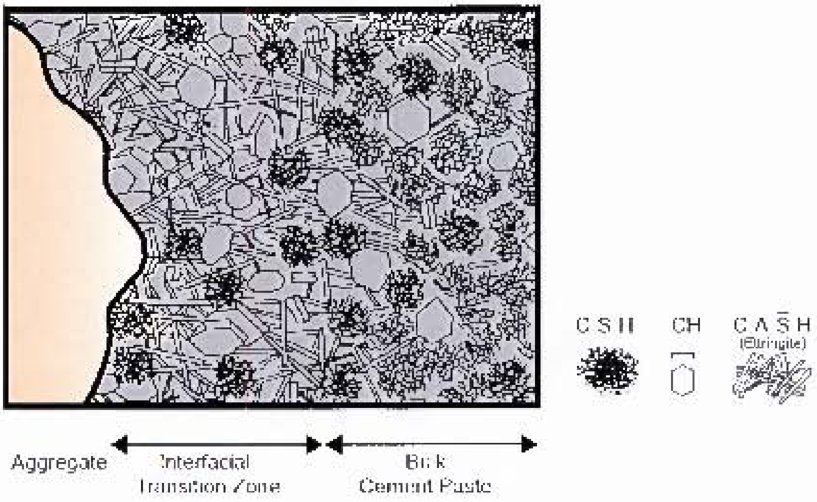


Figure 2.2: Relative pore structure of aggregate, cement paste and ITZ layer (Mehta and Monteiro, 2006)

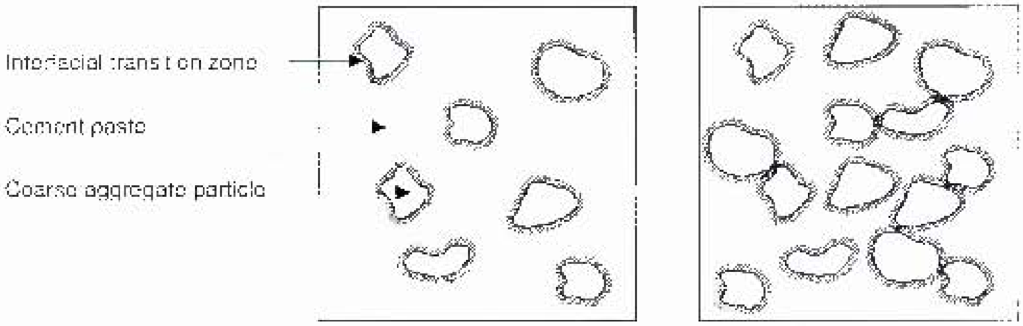
In the description which follows, penetrability and permeability are not used synonymously. Permeability is intentionally highlighted in the discussion of penetrability, as it is the focus of this study.

(i) Coarse aggregate and the interfacial transition zone (ITZ)

Coarse aggregates are often less porous than the cement paste matrix, and hence redirect the flow of ions or molecules around the aggregate and towards the cement paste and ITZ. For most concretes, where satisfactory compaction and curing are performed, the aggregate particles are isolated from the permeability network, and hence do not contribute towards penetrability (Richardson, 2002). This is significant, since natural aggregates commonly have porosities between 0 and 20% (Richardson, 2002), and hence it may be erroneously assumed that the preferential flow path would be through the aggregate particle.

Both the size and quantity of aggregate should be carefully considered, to ensure connectivity of the ITZ is minimised. The ITZ surrounds each coarse aggregate particle and consists of a more porous and penetrable concrete region in comparison with the 'bulk' paste (Ballim et al., 2009). In specific cases, the molecular or ionic transport mechanism will choose to pass directly through the ITZ network (Garboczi, 1995). This is dependent on the amount and size of coarse aggregate in the concrete composite (Schriver et al., 2004).

Figure 2.3 (a) shows a fully compacted concrete matrix consisting of coarse aggregate, cement paste matrix and ITZ layer. In this figure, since the ITZ layers are disconnected, the penetrability of the concrete will usually be governed by the cement paste properties. In Figure 2.3 (b), the quantity of coarse aggregate has been increased, and hence penetrability of the concrete will be governed by both cement paste and ITZ properties. If the amount of aggregate was increased further, a high level connectivity between ITZ layers is expected. At this stage the ITZ layer properties would govern penetrability, and the ITZ becomes percolated (Ballim et al., 2009).



2.3(a) 2.3(b)

Figure 2.3: Penetrability and the interaction between aggregate, paste matrix and ITZ (Alexander and Mindess, 2005)

Only in rare cases (viz. when concrete is extremely dense; ITZ layers are disconnected and the aggregate consists of interconnected pores) will the aggregate properties govern penetrability (Ballim et al., 2009). Aggregate size and quantity do, however, affect the tortuosity of the flow path and hence indirectly affect the total concrete permeability (Schriver et al., 2004).

(ii) Cement paste matrix

The hardened cement paste matrix consists of hydrated (and possibly unhydrated) cement, water and air filled voids. As described above, the paste matrix is commonly considered the governing path for flow of ions or molecules, even though its permeability is lower than that of most natural aggregates. Hence, this region is critical for predicting the permeability of the concrete (Ballim et al., 2009).

The three critical factors governing permeability of the paste matrix are pore size and volume, interconnectivity of pores, and size of penetrating ions or molecules. Figure 2.4 shows the types and relative sizes of pores found in the cement paste. In order to provide a general understanding of the magnitude of these pores, the following description is provided:

- Water-filled gel pores exist at a sub-microscopic level (Brooks, 2003). Gel pores are approximately one order of magnitude (viz. ten times) larger the size of one molecule of water (Neville, 1981).
- Water-filled (or empty) capillary pores, and entrained air pores are at a microscopic level (Brooks, 2003).
- Entrapped air voids are directly visible to the human eye (Ballim et al., 2009).

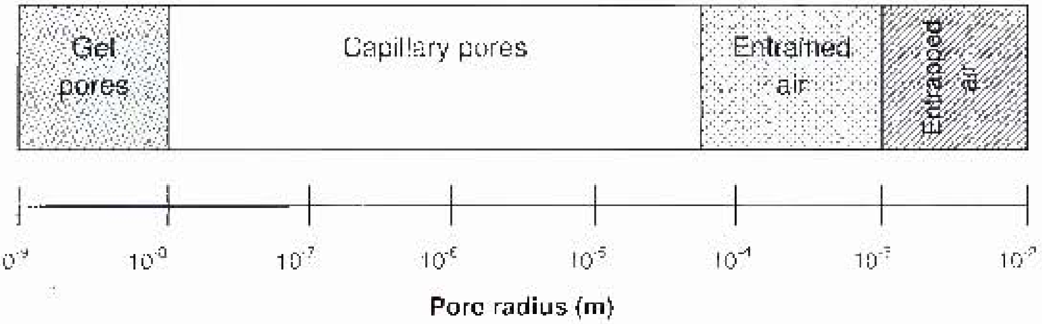


Figure 2.4: Relative pore size in concrete adapted from Richardson (2002)

From Figure 2.4, it can be seen that the pores which exist in concrete can generally be classified by their pore radius. Due to the small pore radius of gel pores, it is accepted that the presence of these pores has little effect on the penetrability of ions and molecules which cause deterioration (Richardson, 2002). This highlights the fundamental difference between porosity and permeability, where the concrete paste matrix is found to be highly porous (high volume of gel pores), but still of low permeability (gel pores too small to allow molecular/ionic flow) (Ballim et al., 2009).

The pore radius of capillary pores for a low w/c ratio may be in the range of 10^{-8} and $10^{-5.2}$ m, while a high w/c ratio generally results in capillary pores between $10^{-5.5}$ and 10^{-4} m (Richardson, 2002). Limiting the capillary pore network is very important for controlling the strength of concrete, as well as penetrability by deleterious ions and molecules (Alexander and Beushausen, 2011). With this in mind, a minimum requirement for improving durability is the specification of a suitably low w/c ratio (Alexander and Beushausen, 2011); ensuring a well-proportioned concrete mix; and providing good compaction and curing practice to ensure full hydration of cement grains (Richardson, 2002).

In comparison to gel and capillary pores, where the concrete mix and curing are fundamental for reducing penetrability, entrained air and entrapped air voids are caused by extrinsic processes of concrete production. The size of these pores is usually greater than that of the penetrating ions and gas molecules, and hence even high quality concrete is inevitably penetrable (Richardson, 2002). The connectivity between pores also plays a critical role in determining the penetrability of the matrix (Schriver et al., 2004). Entrained air voids are dependent on the air-entraining admixtures used, and entrapped air voids are usually dependent on the degree of compaction achieved (Richardson, 2002). Entrained and entrapped air voids are significantly larger than gel and capillary pores, and hence should be minimised if at all possible by good construction practice.

2.2.3 Diffusion

Diffusion may be broadly classified into two groups, namely (i) gaseous and (ii) ionic diffusion. The difference between these two processes relates to the moisture content and diffusing species under consideration (Richardson, 2002). In general, the rate of diffusion is governed by the ionic or molecular concentration gradient, moisture content, temperature, and diffusibility of the concrete (Ballim et al., 2009).

(i) Gaseous diffusion

Gaseous diffusion is defined as the process whereby molecules (such as oxygen or carbon dioxide) move through a porous material under the influence of a concentration gradient (Kropp et al., 1995; Richardson, 2002; Ballim et al., 2009). The transport mechanism involves movement from a high to low concentration (Richardson, 2002). This is accounted for by the negative prefix in Equation 2.1, which describes the direction of the flux (viz. along the negative pressure gradient) (Ballim et al., 2009).

The governing equation for gaseous diffusion under steady state conditions (within a uniformly permeable material), is given by **Fick's first law** of diffusion (Ballim et al., 2009) in Equation 2.1.

$$J = -D_{eff}\frac{dC}{dx} \qquad (2.1)$$

where: J = Mass transport rate (g/m^{2}s)

D_{eff} = Effective diffusion coefficient (m^2/s)

C = Concentration of fluid (g/m^3)

x = Distance (m)

$\frac{dC}{dx}$ = Concentration gradient (g/m^3/m)

The effective diffusion coefficient describes the ability of transfer for a given substance through a solid material (Kropp et al., 1995). For gaseous diffusion, the presence of water molecules in the air voids (moisture content) greatly influences the rate of molecular diffusion. Diffusion rates are significantly higher in the gaseous phase than in solution (Richardson, 2002). Oxygen transport in concrete is one such process, which is largely governed by the gaseous diffusion process (Ballim et al., 2009).

(ii) Ionic diffusion

Ionic diffusion is defined as the process whereby ions (such as chlorides or sulphates) move through a partially or completely saturated porous material under the influence of a concentration gradient (Richardson, 2002; Ballim et al., 2009). The transport mechanism which usually governs the initial ionic ingress is in fact absorption. However, as ingress proceeds diffusion (viz. movement of ions towards the regions of low ionic concentration) becomes the dominant mechanism (Ballim et al., 2009).

The governing equation for ionic diffusion (within a uniformly permeable material), is given by **Fick's second law** of diffusion (Kropp et al., 1995; Richardson, 2002; Mindess et al., 2003; Nilsson, 2003; Ballim et al., 2009) in Equation 2.2.

$$\frac{\partial C}{\partial t} = D_{\text{app}} \frac{\partial^2 C}{dx^2} \quad \text{...} \quad (2.2)$$

where: D_{app} = Apparent substance diffusivity coefficient (m^2/s)

C = Concentration (g/m^3)

t = Time of exposure (s)

x = Distance parameter (depth) (m)

The apparent substance diffusivity coefficent is a function of the flow coefficient and binding capacity (Nilsson, 2003). Ionic diffusion is of particular importance in concrete members exposed to sea water, where chloride ions (from the sea water) diffuse through the covercrete towards the steel reinforcement. As the concentration of chlorides at the steel increases, it approaches the chloride concentration threshold, at which point depassivation of the steel reinforcement initiates (Section 2.3.2) (Ballim et al., 2009). For this reason, the ionic diffusion coefficient of concrete is critical for service life prediction of structures in the marine environment (Ballim et al., 2009).

2.2.4 Sorptivity

Absorption is defined as the process whereby fluids (for example water (H_20)) are drawn into a porous material under the forces of capillary suction (Alexander, 1999; Ballim et al., 2009). Absorption is dependent on the level of saturation of the concrete and the intrinsic concrete pore structure (Alexander, 1999; Ballim et al., 2009). Kropp et al. (1995) provides a description of the non-steady rate of water uptake due to capillary suction.

However, the rate at which the moisture front moves from the exposed surface towards the bulk concrete (under the forces of capillary suction) is termed sorptivity ($mm/min^{0.5}$) (Alexander, 1999). Sorptivity is a useful measurement as it also provides an indication of the interconnectivity of the pore network, in addition to the intrinsic concrete pore structure and level of saturation (Richardson, 2002). The governing equation for sorptivity is given by Equation 2.3 (Richardson, 2002).

$$\frac{V}{A} = S\,t^{0.5} \qquad \text{...} \qquad (2.3)$$

where:

V = Volume of material (H_20) absorbed in time t (mm^3)

A = Cross sectional area of sample in contact with water (mm^2)

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

t = Time (min)

Absorption (which is related to the volume of pore space), and permeability (which is the ease of movement through these pores under pressure) may not be directly related (Richardson, 2002). This is largely due to the connectivity network between pore spaces. Sorptivity may be used to provide a useful measure of surface pore structure and absorption of the covercrete. This relates to the degree of hydration achieved, and the curing efficiency of the covercrete layer (Ballim et al., 2009).

2.2.5 Migration (or conduction)

Migration (otherwise referred to as accelerated diffusion, conduction, or electro-diffusion) is defined as the process whereby ions move under an induced electrical field (Ballim et al., 2009). In this process, positive ions move towards the negative electrode, and negative ions toward the positive electrode. The migration of these electrons results in a concentration difference (in a homogeneous solution), and hence electrical flux (Kropp et al., 1995). Mass transfer in solution is governed by the **Nernst-Planck equation**, as shown in Equation 2.4 (Kropp et al., 1995).

$$J = D\frac{dC}{dx} + \frac{ZF}{RT}DC\frac{dE}{dx} + CV_c \qquad (2.4)$$

where:
J = Mass flux (g/m^2s)
D = Diffusion coefficient (m^2/s)
C = Concentration (g/m^3)
x = Distance (m)
Z = Electrical charge (C)
F = Faraday constant (J/V.mol)
R = Gas constant (J/mol.K)
T = Absolute temperature (K)
E = Electrical potential (V)
V_c = Velocity of solution (m/s)

Equation 2.4 takes into account the movement of ions by diffusion (by concentration gradient), migration (by electrical field) and convection (by permeation) (Kropp et al., 1995).

2.2.6 Permeation

Permeation is defined as the process whereby fluids move through a porous material under an externally applied pressure (Ballim et al., 2009; Holmes et al., 2009). The permeability of concrete is determined by the properties of the permeating fluid, the concrete microstructure, and the moisture condition (Richardson, 2002; Ballim et al., 2009). Of all the previously mentioned concrete transport mechanisms, permeability is considered to have the greatest influence over the vulnerability of RC structures to extrinsic factors (Neville, 1981). It is critical for understanding of attack by freeze/thaw cycles, harmful chemicals, and leaching. It is also important for ensuring watertightness (Neville, 1981) of structures under a constant water head. Visible construction defects such as honeycombing, cracking and poor construction joints provide pathways of increased permeability towards the bulk concrete (Neville, 1981), and hence should be minimised by improved construction practice wherever possible.

The term permeation, however, is often erroneously used to account for all transport mechanisms which affect concrete ingress. Recall, that actions such as capillary absorption are fundamentally different, and are dependent on different concrete material properties (Richardson, 2002). However, reducing the permeability of the covercrete does improve durability (for permeability-related deterioration processes as well as other processes linked to fluid transfer), and hence a suitable minimum requirement for ensuring the durability RC structures, is to ensure the covercrete is relatively impermeable (Neville, 1981).

Permeability is also often confused with the porosity of concrete. Porosity is defined as a measure of the proportion of voids in the concrete, while permeability is a measure of the ability of molecules or ions to move through concrete. In particular, permeability is dependent on porosity, size, distribution and connectivity of pores, and not merely the proportion of air pore volume (Neville, 1981).

In the preceding discussion, water permeation and vapour (air) permeation have been discussed together as fluid penetration mechanisms. However, there is no unique relationship between gas and water permeability in concrete (Neville, 1981). In addition, concrete is approximately 10 to 100 times more permeable to gas than water (Mindess et al., 2003). For this reason, each of these processes will be discussed individually.

(i) Gas permeation

Gas permeation is of particular interest where airtightness is of great importance, or where the concrete structure exists under constant internal pressure. For example, in the case of a nuclear containment building, the chamber is pressurised and acts as a critical barrier to prevent radiation leakages. Gas permeation is also used extensively to predict various deterioration processes in concrete, such as carbonation (Ballim et al., 2009).

Concrete may be considerably more permeable to some fluids (such as air) than others, however, literature explaining this phenomenon is quite limited. In addition to the influence of gas type, it should also be noted that most concrete (in its natural environment) will be inherently moist. If the capillary pores are partially filled with water, then the path available for gas permeation is decreased (Neville, 1981). For this reason, the moisture condition should be carefully considered when investigating the gas permeability of concrete (see Section 2.7.1).

Assuming the laminar flow of gas through the concrete, gas permeation may be evaluated according to Equation 2.5 (Kropp and Alexander, 2007), based on the **Hagen-Poiseuille relation** for Newtonian fluids through a cylindrical tube (Kropp et al., 1995; Kropp and Alexander, 2007).

$$k = \mu \frac{Q}{t} \frac{L}{A} \frac{2p}{(p_1 - p_2)(p_1 + p_2)} \quad \text{..} \quad (2.5)$$

where: k = Coefficient of gas permeability (m^2)
Q = Volume of gas flowing (m^3)
μ = Viscosity of gas (Ns/m^2)
L = Thickness of the sample (m)
A = Permeated area (m^2)
p = Pressure at which volume Q is measured (N/m^2)
p_1 = Pressure at entry of gas (N/m^2)
p_2 = Pressure at exit of gas (N/m^2)
t = Time (s)

This was derived by relating the measured flow volume to a corresponding gas pressure (Zager, 1955). The factors which affect gas permeation are mostly the same as those for water permeation. However, it is important to note that equilibrium for gas permeation is reached within a few hours, as opposed to around 10 days for water permeation (Neville, 1981). The relative time required to reach equilibrium is also very dependent on the element thickness.

(ii) Water permeation

In consideration of the durability of RC structures, the most important liquid commonly penetrating concrete structures is water (Kropp and Alexander, 2007). As shown in Equation 2.6, water permeation is expressed as a coefficient of permeability, K$_w$ (m/s). This was developed empirically by D'Arcy, and termed **D'Arcy's law** and D'Arcy's coefficient (Neville, 1981). However, this formula does assume laminar flow of an incompressible fluid, and also neglects the viscosity of water. This is a considerable simplification to the actual governing equation (Kropp et al., 1995; Kropp and Alexander, 2007).

$$\frac{dq}{dt} = K_w \frac{\Delta h}{L} \frac{1}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.6)$$

where: $\frac{dq}{dt}$ = Rate of water flow (m^3/s)
A = Cross-sectional area of the sample (m^2)
Δh = Drop in hydraulic head through the sample (m)
L = Thickness of the sample (m)

Water permeation is particularly important for water retaining structures, such as dams, where moisture transport through the structure may be detrimental (Neville, 1981; Ballim et al., 2009).

2.2.7 Combined transport mechanisms

It is convenient to isolate each of the apparent or effective transport processes, such that a simplified analysis may be performed (Kropp and Alexander, 2007). However, damage is rarely due to one isolated cause (Neville, 1981). For this reason, careful attention should be paid to all transport mechanisms which are taking place, as multiple processes may be acting along the same (or different) flow paths, and in the same (or possibly opposite) directions (Hilsdorf, 1995; Ballim et al., 2009). Such mechanisms are referred to as mixed modes of transport (Kropp and Alexander, 2007).

For example, in the case of ingress of dissolved chloride ions, the concrete surface region may consist of partially water-filled voids, and hence absorption being the governing transport mechanism. However, deeper into the concrete member, the capillary voids may be completely saturated, and hence diffusion the governing transport mechanism (Kropp and Alexander, 2007). Another example of a common type of combined transport mechanism would be a parking garage near the ocean. In this case both carbonation (linked to permeation) and chloride ingress (diffusion) occur together within the covercrete layer. The relationship between carbonation, diffusion and permeation will be discussed in Section 2.4.3.

Lastly, another mixed mode of transport is that of convection, whereby air-flow through a relatively dry concrete, is effectively carried with the air stream, even though the air stream itself may move by permeation (Nilsson, 2003).

2.2.8 The effect of aging on transport properties

As concrete ages, so its intrinsic properties also change. The concrete porosity generally decreases as a result of the ongoing hydration of cement grains, as well as due to the reduction in pore interconnectivity (Kropp and Alexander, 2007). Drying shrinkage, as well as corrosive interactions with the environment over time (e.g. a harbour wall in the splash zone), may result in further microcracking by the concrete paste matrix (Kropp and Alexander, 2007). In addition to these actions, the degradation due to certain processes, such as leaching, further increases the porosity of the concrete paste matrix, lowering the resistance to ingress of harmful substances.

In combination, these effects modify the concrete properties and should be accounted for if time-dependent service life prediction is performed based on tests on young concretes (Kropp and Alexander, 2007; Ballim et al., 2009). For this reason time-dependent coefficients, such as that for diffusion, have been developed (Ballim et al., 2009) to accommodate for such effects.

2.3 Deterioration of reinforced concrete structures

Durability, as defined by ISO 13823: 2008 (2012), is the "capability of a structure or any component to satisfy, with planned maintenance, the design performance requirements over a specified period of time under the influence of environmental actions, or as a result of a self-ageing process".

In the past, much of the focus was placed on building structures which are sufficiently strong and robust. For this reason, very few cases of structural failure (for example by member collapse) are seen in modern RC structures (Torrent et al., 2007). On the other hand, the deterioration of many RC structures (and the subsequent durability of RC structures) has been deemed unsatisfactory (Alexander et al, 2008). For this reason, RC structures are often requiring extensive repair and rehabilitation to sustain the structure in order that its intended design service life is achieved (Torrent et al., 2007; Alexander et al., 2008).

As noted by Torrent et al. (2007), many papers are available which describe the social and economic consequences of poor durability. The problems associated with poor durability have been recognised in the US, Europe (Torrent et al., 2007) and Japan (Imamoto et al., 2008), to mention a few. In Europe, approximately half of total construction expenditure is directed towards repair and rehabilitation (Long et al., 2001; Torrent et al., 2007), much of which could have been prevented through improved durability-based design, construction and monitoring.

In most cases, damage to structures occurs as a result of poor durability, and not insufficient strength (Torrent and Jacobs, 2009). The misconception, that high compressive strengths will result in durable structures, is still embraced by many engineers today (Kollek, 1989). While compressive strength is important for structural stability, the durability-related transport mechanisms are equally important. The durability of RC structures is commonly associated with resistance to carbonation and chloride-induced corrosion. These are dependent on the quality of the covercrete layer and cover depth (Richardson, 2002). Therefore, durability is affected not only by mix design properties, but also the quality of construction practice (Torrent and Jacobs, 2009).

Durability monitoring plays a crucial role in ensuring that design and construction is performed in accordance with the durability-related specifications. It should be noted that good durability is not intended to be 'maintenance-free' concrete (Richardson, 2002), as this may result in a substantial over-design. The aim of providing durable RC structures is closely associated with the aims of sustainability, whereby the needs for infrastructure are met, without depleting resources (e.g. aggregates or cement) or providing structures which will require extensive time, money and expertise to maintain. This has been the conceptual basis for improving the durability of RC structures, and has led to the shift from prescriptive ('recipe-like') specifications to performance based approaches. Performance-based specifications provide a means for evaluating a RC structure in service, and allowing the prediction of the expected service life.

Further, performance-based monitoring allows corrective action to be performed before the rate of deterioration becomes excessive. It has been found that the costs of corrective action increase exponentially with time (before corrective action) (Torrent et al., 2007). The effect of delayed repair and rehabilitation is further described by De Sitters "Law of Fives" (as of 1984). The "Law of Fives" highlights the compounding monetary effect of delayed maintenance (Vanier, 2001). In particular, 1 dollar spent on ensuring good quality design and construction is as effective as 5 dollars after construction, but before corrosion; 25 dollars after construction, after minimal corrosion has onset; and 125 dollars after construction, when widespread corrosion has onset (Wilmot, 2007). This again highlights the importance of performance-based durability monitoring, and early detection of maintenance of deterioration.

2.3.1 Corrosion of reinforcement in concrete

Durability is commonly associated with the rate of ingress of harmful ions or molecules, and the subsequent detrimental action of these species on concrete and/or the reinforcing steel (Torrent et al., 2007). In general, corrosion occurs when a metal is placed in a reactive environment in the presence of moisture and oxygen, at which point surface wastage occurs. Further, the optimum relative humidity for corrosion has been found to be between 70 and 80% (Neville, 2011). The corrosion product is of a lower density than the original metal, and hence localised expansion occurs (Richardson, 2002). This expansion leads to further cracking, spalling and deterioration of the covercrete.

The covercrete may be viewed as a protective barrier to the steel, which slows the ingress of harmful agents, and hence delays the onset of corrosion of the reinforcing steel. The penetrability of the covercrete, which governs the transport of ions and molecules, restricts the movement of moisture and oxygen and hence governs the rate of corrosion (Richardson, 2002).

The high alkanity ($13 < pH < 14$) of the pore solution which surrounds the steel reinforcement (Tuutti, 1982), results in the formation of dense, thin (1-10nm) ferric oxide film (maghemite, γ - Fe_2O_3), which prevents contact of the reinforcing steel with oxygen or moisture (Neville, 2011). The source of the alkalis in the pore water is primarily the cement paste (Oberholster, 2009). Hardened cement contains sodium and potassium hydroxides (NaOH and KOH), which dissolve easily into the pore water (Oberholster, 2009). By dissolution, high concentrations of sodium, potassium and hydroxyl ions create a highly alkali pore solution (Oberholster, 2009). Due to the high alkalinity of the pore solution, negligible corrosion takes place without the presence of harmful species. However, as depassivation occurs the ferric oxide film breaks down, and hence the onset of corrosion (Richardson, 2002).

The ferric oxide layer may be disrupted by two mechanisms (Ballim et al., 2009):

1. Reduction in the concrete alkalinity around the steel, due to carbonation or other acid attack. The free hydroxyl ion concentration becomes insuffient to protect the ferric oxide layer.
2. Direct contact with aggressive ionic solutions such as chlorides, which enable metallic dissolution.

After the ferric oxide layer has been disrupted, corrosion may initiate depending on the environment surrounding the steel. In the case of corrosion due to a lowered concrete alkalinity, the pH should be lowered to about 9.0 (Neville, 2011). In the case of contact with aggressive salts, the concentration of salts in the environment should exceed a certain limiting concentration (depending on the chemical). This concentration is commonly termed the corrosion 'threshold' (Neville, 2011). Figure 2.5 shows the transport of various harmful substances which result in steel corrosion.

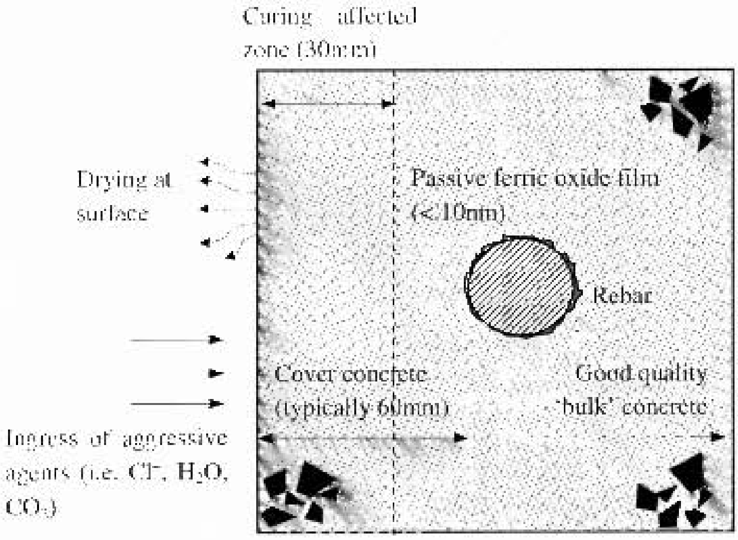


Figure 2.5: Chemical processes acting on covercrete section adapted from Alexander et al., (2007)

For an electrochemical corrosion process to take place, anodic and cathodic regions are required. At the anode corrosion occurs. Along the reinforcing steel a transfer of electrons occurs, in the direction of anode to cathode. However, from cathode to anode exists a transfer of hydroxl ions through the concrete pore solution (Neville, 2011). The rate at which corrosion takes place is largely determined by availability of water and oxygen in the concrete surrounding the steel. This process is shown in Figure 2.6.

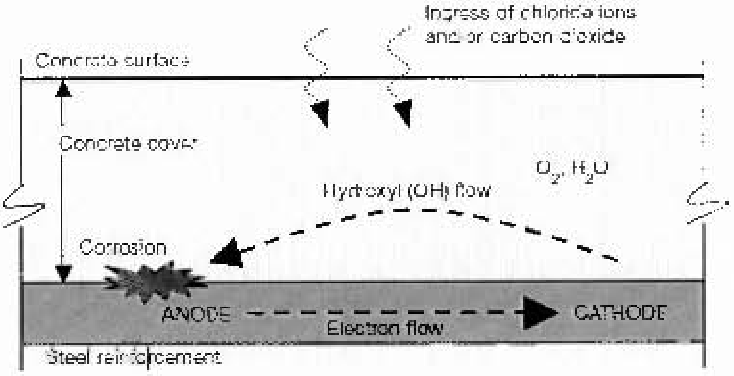


Figure 2.6: The steel corrosion process in concrete (Beushausen and Alexander, 2009)

Corrosion propagation (after disruption of the ferric oxide layer) is quite similar, regardless of the corrosion-initiation mechanism. Initially the steel is dissolved into solution, hence giving up electrons at the anode (Ballim et al., 2009). Thereafter, in the presence of water and oxygen, hydroxl ions move back towards the anode. In this way an electrochemical cell is initated (Ballim et al., 2009). The governing equations for reactions at the anode and cathode are shown in Equations 2.7 and 2.8 respectively (Mackechnie and Alexander, 2001; Ballim et al., 2009).

Anode: $Fe \rightarrow Fe^{2+} + 2e^-$ .... (2.7)

Cathode: $2H_2O + O_2 + 4e^- \rightarrow 4OH^-$ .... (2.8)

A number of additional oxidation stages take place, resulting in a product called hydrated ferric oxide (viz. $2Fe(OH)_3$). This compound has the ability to swell up to approximately 10 times its original size, placing the surrounding concrete (in particular the covercrete) in tension, and may result in cracking, delamination or spalling (Ballim et al., 2009).

Carbonation and chloride-induced corrosion are commonly termed general and pitting corrosion respectively, due to the visible deterioration at the concrete surface during the propagation phase. General corrosion (also termed microcell corrosion) occurs, when corrosion sites adjacent to one another are of equal size. Pitting corrosion (also termed macrocell corrosion) occurs when the anode is significantly smaller than the cathode, which leads to areas of very high localised corrosion (Ballim et al., 2009). The corrosion mechanism is also affected by intrinsic concrete properties (such as resistivity), as well as by cover depth and moisture content (Mackechnie and Alexander, 2001; Ballim et al., 2009).

Reinforcement corrosion is not usually identifiable at the onset. However, with time visable defects may give indication of the type and severity of the underlying corrosion. The type of corrosion may (in some cases) be determined by the environmental exposure, however, the appearance also provides an indication of corrosion mechanism (Richardson, 2002). The progression of visible defects due to reinforcement corrosion usually appears in the order of surface cracking, rust staining and thereafter spalling. Carbonation-induced corrosion is typically less severe than chloride-induced corrosion (and also less costly to repair), with small amounts of pitting occuring along the reinforcement bar (Richardson, 2002; Beushausen, 2010). On the other hand, chloride-induced corrosion usually exhibits clear anodic and cathodic sites, with significantly more severe pitting. Carbonation-induced corrosion is, however, unlikely to affect structural integrity, while chloride-induced corrosion has the potential for significant structural strength loss, and if not addressed timeously even structural instability (Beushausen, 2010).

2.3.2 Overview of deterioration mechanisms in reinforced concrete

Deterioration mechanisms may be broadly classified as chemical, physical, or electrochemical attack (Nilsson, 2003; Ballim et al., 2009). The three common durability-related chemical (or electrochemical) deterioration mechanisms are carbonation-induced corrosion; chloride-induced corrosion and the chemical attack of concrete (e.g. by sulphates) (Torrent et al., 2007). In this study, only carbonation and chloride-induced corrosion will be described in detail, due to the importance of these mechanisms in the DI approach, as currently adopted for performance-based specification of durability in South Africa.

(i) Carbonation-induced steel corrosion

Carbonation is a common deterioration mechanism which occurs in RC structures exposed to carbon dioxide (CO_2). The reaction between carbon dioxide and water in the capillary pores forms carbonic acid ($H_2O + CO_2 \leftrightarrow H_2CO_3$) (Ballim et al., 2009). This lowers the pH from above 12.5 to below 9.0 (Tuutti, 1982; Richardson, 2002). In combination with the availability of water and oxygen, the lowering of pore water pH creates an environment conducive to corrosion (Neville, 2011). Thereafter, the carbonic acid reacts with the hydrated (and unhydrated) cement particles, specifically calcium hydroxide ($Ca(OH)_2$), to form calcium carbonate ($CaCO_3$). Breakdown of the passive ferric oxide layer then takes place, and subsequently an electrochemical cell is developed (Richardson, 2002).

The fundamental reaction describing the carbonation process is given by Equation 2.9 (Richardson, 2002; Ballim et al., 2009).

$$Ca(OH)_2 + CO_2 \xrightarrow{H_2O} CaCO_3 + H_2O \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.9)$$

As shown in Figure 2.7, the carbon dioxide moves by diffusion deeper into the concrete, and results in a carbonated zone. The leading edge of this zone is usually termed the 'carbonation front' (Richardson, 2002). An important requirement for carbonation is the partial water saturation of capillary pores. The reported highest levels of carbonation are achieved when relative humidity in capillaries lies between 50 and 75% (Neville, 2011). If the carbonation front is allowed to reach the reinforcing steel, depassivation is initiated.

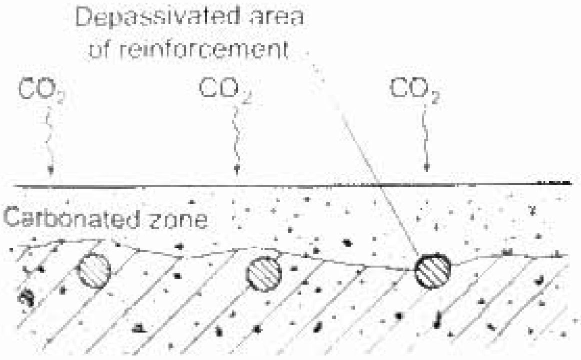


Figure 2.7: Schematic of carbonation-induced steel corrosion (Richardson, 2002)

Carbonation is unlikely to be responsible for loss of structural integrity, but may result in unsightly cracking, spalling and delamination of RC structures (Richardson, 2002). It is also regarded as a relatively slow process, in comparison with other deterioration mechanisms, for example chloride-induced corrosion (Richardson, 2002). However, it is a very important durability concern, as it occurs with almost all RC structures (even if at a very slow rate), regardless of type of structure and location. This is due to the inherent presence of carbon dioxide in the atmosphere. This does not imply, however, that carbonation will be the governing (most severe) deterioration mechanism in all cases.

Carbonation is primarily influenced by diffusibility (or permeability), reserve alkalinity, environmental carbon dioxide content and exposure condition (Richardson, 2002). Carbon dioxide content is highest for industrial areas and inside buildings (Richardson, 2002), in particular parking garages. The process of carbonation, its contributing factors, and current carbonation-based service life models are critical aspects for the study which follows, and hence will be discussed in detail in Section 2.4.

(ii) Chloride-induced steel corrosion

Chloride-induced steel corrosion is recognised as the most severe deterioration mechanism in RC structures. Further, if adequate measures are not taken, chlorides have the potential to result in significant losses in structural load-bearing capacity (Richardson, 2002). Chloride contamination may occur during mixing, or as a result of covercrete ingress in marine (or coastal) environments, or where de-icing salts are used. Contact of the chlorides with the concrete surface may be in the form of water (or air) transported salts (Ballim et al., 2009). The chloride ions cause depassivation of the ferric oxide layer (Fe_2O_3), and thereafter act as a catalyst (by ferric hydroxide precipitation) to accelerate the corrosion process (Ballim et al., 2009). Figure 2.8 shows the ingress of chloride ions and the subsequent electrochemical process.

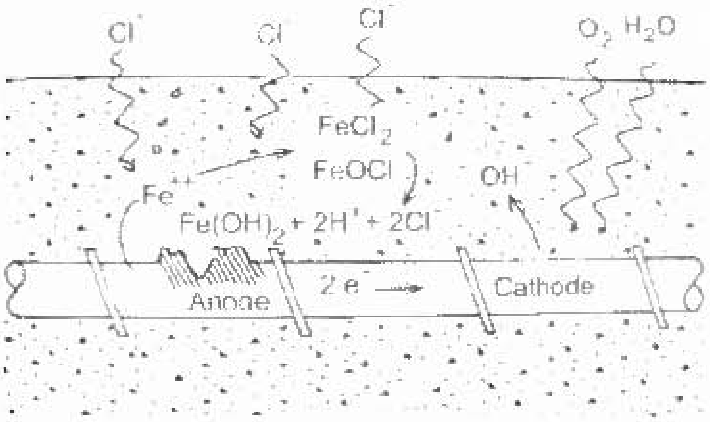


Figure 2.8: Schematic of chloride-induced steel corrosion (Richardson, 2002)

It should be noted that reactions describing the interaction between reinforcing steel and passive ferric oxide film (maghemite, γ - Fe_2O_3) are not fully understood (Richardson, 2002). In general, this process is governed by both intrinsic (including w/c ratio, chloride binding ability, penetrability) and extrinsic (including chloride content at surface, temperature) factors (Mackechnie, 1997; Richardson, 2002). Chloride binding ability of cement extenders, such as GGBS, FA and CSF, is of particular importance, as it significantly slows the rate of chloride ingress (Mackechnie, 1997; Ballim et al., 2009). Another of the important intrinsic factors for chloride-induced corrosion rate is the chloride ion to hydroxyl ion ratio (Richardson, 2002), which will be discussed in Section 2.4.2.

2.4 Fundamental principles of carbonation

An introduction to carbonation has been provided in Section 2.3.2 (i). This section aims to provide a detailed description of the chemistry, contributing factors and the mathematical representation of the carbonation process. This section gives an essential description of the carbonation phenomenon, and hence insight into the sensitivity of carbonation to various intrinsic and extrinsic factors.

2.4.1 Chemistry of carbonation

As discussed in Section 2.2.1, the cement paste properties of the covercrete largely govern penetrability, and subsequently the rate at which the carbonation front moves towards the bulk concrete. Further, the penetrability also governs the rate at which corrosion proceeds after depassivation has taken place.

Common cements (and cement extenders) used in South Africa are Portland cement (PC), ground granulated blastfurnace slag (GGBS), condensed silica fume (CSF) and fly ash (FA). A number of cementing reactions take place in the hydration of PC (Grieve, 2009), however, these will not be discussed in detail, apart from those which suffice to aid description of the carbonation process.

The primary cementing reaction, in terms of strength development, is described by the hydration of calcium silicate and water to form calcium silicate hydrates and calcium hydroxide (Alexander and Beushausen, 2011). In particular, this consists of the reactions by both dicalcium and tricalcium silicate with water to form calcium silicate hydrates and calcium hydroxide (Alexander and Beushausen, 2011). For common CEM I cements in South Africa, the dicalcium and tricalcium contents are approximately 60-73 % and 8-30 % respectively (Grieve, 2009).

The reactions for dicalcium and tricalcium silicate are described by Equations 2.10 and 2.11, respectively (Grieve, 2009; Alexander and Beushausen, 2011):

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \tag{2.10}$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \tag{2.11}$$

Where:

C - CaO, calcium oxide
S - SiO_2, silica
A - Al_2O_3, alumina
F - Fe_2O_3, ferric oxide
H - H_2O, water

The following compounds are described:

C_3S - Tricalcium silicate
C_2S - Dicalcium silicate

The development of calcium silicate hydrates is considered the principle reason for increasing paste strength, and also the reduction in porosity (Alexander and Beushausen, 2011). In addition, the permeability of the concrete paste also decreases, which has an important effect on the rate of carbonation. Figure 2.9 shows relationship between hydration of the cement paste, strength, porosity and permeability over time (Mehta and Monteiro, 2006). The importance of adequate hydration (which is largely dependent on curing) is also evident. This will be addressed in Section 2.5.6.

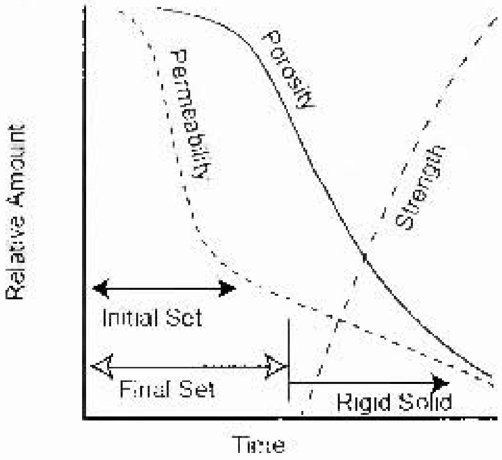


Figure 2.9: Influence of hydration on permeability, strength and porosity (Mehta and Monteiro, 2006)

In addition to the reduction of permeability (and porosity) of the cement paste, the hydration reaction also results in the production of calcium hydroxide ($Ca(OH)_2$) (Richardson, 2002) as shown in Figure 2.10.

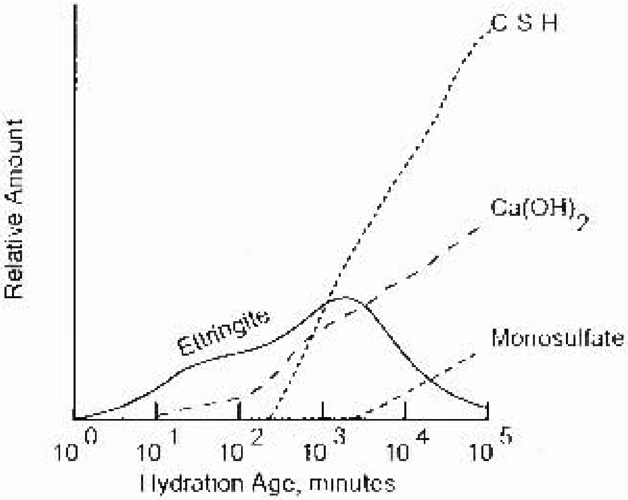


Figure 2.10: Formation of hydration products in Portland cement (Mehta and Monteiro, 2006)

The fundamental carbonation equation is given by Equation 2.9, however, this process may be separated into sub-processes for the dissolution of calcium hydroxide, and thereafter the production of calcium carbonate (Richardson, 2002).

1. The first reaction describes the dissolution of calcium hydroxide (Equations 2.10 and 2.11), due to free water in the concrete capillary pores. This is given by Equation 2.12.

$$\text{Ca}(OH)_2 \xrightarrow{H_2O} Ca^{2+} + 2\,OH^- \quad \ldots\ldots \quad (2.12)$$

2. Thereafter, the carbon dioxide reacts with the product ions and results in the production of calcium carbonate ($CaCO_3$), given by Equation 2.13.

$$Ca^{2+} + 2\,OH^{-} + CO_2 \rightarrow CaCO_3 + H_2O \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.13)$$

The formation of calcium carbonate reduces the hydroxyl ion (OH^-) concentration, and hence reduces the alkalinity (pH) of the paste (in particular the alkalinity of pore water). This process creates an environment which is conducive to depassivation of the ferric oxide layer which protects the reinforcing steel (Richardson, 2002). Carbon dioxide has the ability to react with both hydrated and unhydrated cement particles, however, the former is more important with regard to predictions of durability by carbonation (Richardson, 2002).

The calcium carbonate ($CaCO_3$) produced through carbonation occupies a greater volume than the reacting constituents (Richardson, 2002), and hence results in a reduction in porosity and permeability (Neville, 1981; Ollivier et al., 1995; Claisse et al., 1999). Further, carbonation also increases the compressive strength of concrete (Hilsdorf, 1995). These are considered beneficial aspects of carbonation in terms of improving durability (Richardson, 2002; Neville, 2011), however, these effects should be carefully considered for surface tests (such as that for permeability) as the reduced permeability (or increased strength) may be misleading (Claisse et al., 1999).

2.4.2 Factors influencing the rate of carbonation

The carbonation rate is governed by the diffusivity of concrete (this will be elaborated on later); the reserve alkalinity of the concrete; the carbon dioxide concentration at the surface, and exposure condition of the RC structure (Richardson, 2002). In this section the governing factors will be described briefly, only to suffice explanation of carbonation-based service life prediction models presented.

Reserve alkalinity refers to the ability of the concrete to resist the reaction involving hydroxyl ions to form calcium carbonates (Equation 2.12). In this way, reserve alkalinity slows the movement of the carbonation front (viz. the region where the pH has dropped below approximately 9.0) by acting a 'pH buffer' (Richardson, 2002). The factors which affect reserve alkalinity may be summarised as follows (Richardson, 2002; Ballim et al., 2009):

- Cement type: The addition of cement extenders (such as GGBS and FA) to PC reduces the total calcium oxide content, and subsequently the calcium hydroxide content of the concrete (Neville, 1981; Glass, 2003). This results in a reduced pH buffer. However, the use of extenders also reduces permeability, hence, a balance between the two is critical for ensuring resistance to carbonation (Richardson, 2002).
- Adjusting w/c ratio: For a given mix design, reducing the w/c ratio increases the PC content, which increases the cement content. A higher cement content results in a higher calcium hydroxide content (and strength). This results in a higher

reserve alkalinity (Richardson, 2002). However, research has shown that carbonation rate is not sensitive to cement content at a given w/c ratio, due to a number of competing processes (Wassermann et al., 2009). In addition, a well-cured concrete of sufficiently low w/c ratio is unlikely to incur a carbonated zone exceeding 25 mm (Mindess et al., 2003), owing primarily to its low permeability. If a sufficiently low w/c ratio is achieved, even in a fully carbonated concrete (after depassivation), corrosion may still not be a concern due to the high impermeability of the hardened concrete (Mindess et al., 2003).

The rate of carbonation is also closely related to the carbon dioxide concentration at the surface (Tuutti, 1982; Richardson, 2002). There is a general decrease in carbon dioxide concentration from dense urban regions to rural and coastal regions (Richardson, 2002). It should be noted, however, that designing structures closer to the ocean (or near marine environments) will usually shift emphasis from deterioration due to carbon dioxide to that of chloride-induced steel corrosion. It may also be difficult to generalise carbon dioxide concentration for an entire structure, as localised exposure will inevitably govern carbonation rate (e.g. consider an underground parking garage).

As mentioned previously, carbonation rate is also largely affected by relative humidity inside the concrete pore network. Carbonation rate is highest at approximately 50 to 75% relative humidity (Neville, 2011), whereas steel corrosion rate is greatest at approximately 80% relative humidity (Richardson, 2002). If the relative humidity is below 50%, restricted dissolution of the calcium hydroxide slows carbonation rate. In addition, if the relative humidity exceeds 80%, the pores become less permeable due to the 'pore blocking' effect of moisture. For this reason, the exposure conditions should ideally be classified in terms of both carbon dioxide concentration and relative humidity, as it is a combination of these effects which ultimately governs the carbonation rate (Richardson, 2002).

An example of the environmental classes for structures subject to carbonation-induced corrosion is given by EN 206-1 (2000). The exposure condition is given as a function of the expected wetting and drying cycle, which is acknowledged as one of the most important factors for predicting carbonation rate (Tuutti, 1982; Glass, 2003; Nilsson, 2003). An extract from the BS EN 206-1 exposure classes (for carbonation-induced corrosion only) is shown in Table 2.1.

Table 2.1: Environmental classes for carbonation-induced corrosion (BS EN 206-1, 2000)

2. Corrosion induced by corrosion		
Where concrete containing reinforcement or other embedded metal is exposed to air and moisture, the exposure shall be classified as follows: NOTE The moisture condition relates to that in concrete cover to reinforcement or other embedded metal, but in many cases, conditions in the concrete cover can be taken as reflecting that in the surrounding environment. In these cases classification of the surrounding environment may be adequate. This may not be the case if there is a barrier between concrete and its environment		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long term water contact 'Many' foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

With respect to the quality of site work performed, carbonation rate is largely affected by the curing efficiency (Section 2.5.6) and degree of compaction (Section 2.5.5) achieved. Poor compaction results in the presence of entrapped air voids (Section 2.2.2), and hence increases the permeability of concrete. Surface cracking due to structural flaws (deflection cracking) or poor durability (e.g. shrinkage) further increases permeation, and hence the rate of carbonation (Ballim et al., 2009).

2.4.3 Mathematical representation of carbonation

Diffusion is defined as the process whereby ions or molecules move through a porous material under the influence of a concentration gradient (Richardson, 2002; Ballim et al., 2009). The bulk concrete is considered the region of low carbon dioxide concentration, while the carbon dioxide exposure at the surface is considered the region of high concentration. This concentration gradient results in a carbon dioxide flux, moving from high to low regions (Tuutti, 1982; Ballim et al., 2009). As shown in Figure 2.11, initially the reaction involves development of this carbonation front. Thereafter, the front moves deeper towards the bulk concrete (Ballim et al., 2009).

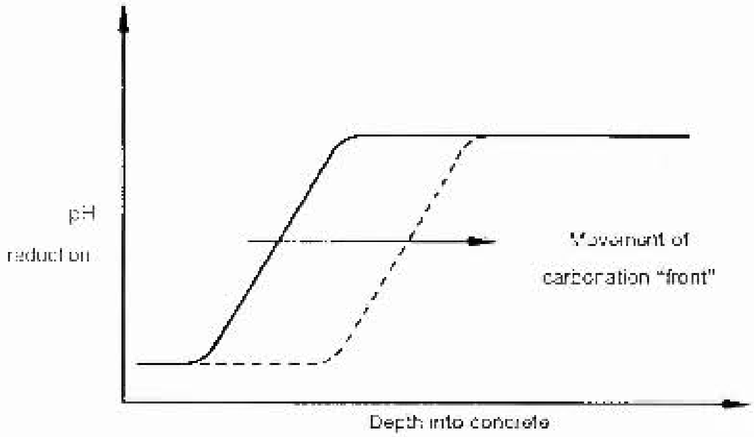


Figure 2.11: Pore alkalinity (pH) reduction due to carbonation front (Ballim et al., 2009)

Much research has been performed, resulting in a number of carbonation depth prediction models, which take into account variables such as carbon dioxide concentration, amount of alkaline material, wetting and drying cycles, as well as calcium carbonate production through the carbonation reaction (Richardson, 2002; Neville, 2011). Under steady hygrometric (humidity) conditions, the generally accepted empirical relationship describing this process is given by Equation 2.14 (Richardson, 2002; Ballim et al., 2009; Neville, 2011).

$$x = Dt^n \qquad (2.14)$$

where: x = Depth of carbonation (mm)

n = Constant describing exposure condition (between 0.4 and 0.6). The variable n is commonly taken as 0.5, and termed the "square root relationship".

D = Carbonation coefficient (mm/year^n)

t = Time of exposure (years)

In the DI approach model presented by Mackechnie (1999), prediction of carbonation depth using the oxygen permeability index (this test method is discussed in Section 2.6.4) is presented. This model is currently used in South Africa to perform durability predictions. In accordance with Equation 2.14, the South African prediction states that D (mm/year^n) is dependent on OPI value and environmental exposure class, while n (between 0.1 and 0.4) is dependent on the binder type used (Mackechnie, 1999).

It has been recognised, however, that a relationship exists between permeation and diffusion, which has significant implications for modelling of the carbonation rate (Nilsson and Luping, 1995; Salvoldi, 2010; Neville, 2011). The theoretical relationship between permeability and diffusivity coefficients is given by Equation 2.15 (Nilsson and Luping, 1995). In this equation, the parameter b is dependent on the substance transported.

$$K = constant \times D^{b} \quad \text{(2.15)}$$

where:
K = Permeability coefficient (in m^2 or m^2/s)
D = Diffusivity coefficient (m^2/s)
b = Parameter related to substance transported

The relationship is dependent on the substance type (viz. ion or molecule), substance phase (viz. gas, vapour or liquid), as well as the moisture content inside the pore network. In particular, for gas permeation, the moisture within the pore network results in a 'blocking' of the gas particles (Nilsson and Luping, 1995), and hence a reduced permeability. Equation 2.15 still requires refinement (Nilsson and Luping, 1995), however, it does lend support to the use of permeation to model what is effectively a diffusion process (Parrott, 1994; Richardson, 2002; Neville, 2012). The benefits of using permeation as the transport mechanism for carbonation are twofold (Richardson, 2002):

- The means for achieving low permeability concretes are well known. These include appropriate cement and cement extender type, w/c ratio, curing and compaction.
- There are numerous non-destructive on-site and laboratory-based test methods for permeation, which require less time to perform and yet still provide good, representative results.

In a recent study performed by Salvoldi (2010), the relationship between concrete diffusion and permeability was investigated. A unique relationship was found which related the effective dry diffusion coefficient with k_{OPI} (k-value from the OPI test). This relationship is given by Equation 2.16 (Salvoldi, 2010).

$$D_{dry} = \left[1.4 \times \left(\frac{k_{OPI}}{10^{-11}}\right)^{2.2}\right] \times 10^{-11} \quad \text{(2.16)}$$

where:
D_{dry} = Effective dry diffusion coefficient
k_{OPI} = k-value from the OPI test

In addition to the relationship between effective dry diffusion coefficient with oxygen permeability index (k-value), a conceptual framework was presented, as an improvement to that of Mackechnie (1999) for the DI approach. The mathematical model proposed by Salvoldi (2010) for the prediction of carbonation depth based primarily on the k_{OPI}-value is given in Equation 2.17.

$$x = \sqrt{\frac{2\,D_{dry} c\,\beta}{a}} \times \sqrt{t_e} \quad \ldots\ldots (2.17)$$

where:
x = Carbonation depth (mm)
D_{dry} = Effective dry diffusion coefficient (m^2/s)
k_{OPI} = k-value from the OPI test (m/s)
c = Ambient carbon dioxide concentration (mol/m^3),
β = Relative humidity factor
a = Amount of carbonatable material in the concrete matrix (mol/m^3)
t_e = Effective time of carbonation over the service life of the concrete (years)

The variables and respective parameters for Equation 2.17 are described in the study by Salvoldi (2010). Equations 2.16 and 2.17 allow the prediction of carbonation depth, primarily based on the k_{OPI}-value (k-value from the OPI test).

2.4.4 Carbonation-based service life prediction

Much theoretical and empirical work has been performed in order to develop models which can be used to predict the service life of RC structures (Richardson, 2002). More recently, service life prediction models use the measurement of gas-permeation which is related either analytically to diffusion, or empirically to carbonation rate (Kropp, 1995; Ballim et al., 2009).

Richardson (2002) presents two carbonation depth prediction models. The first is that of Parrot (1994), based on the diffusion principles of carbonation (Tuutti, 1982; Richardson, 2002). Parrot's method presents an improvement to the general square root relationship for diffusion (Equation 2.14) as the basis for service life prediction. In this model, the following key assumptions are made (Parrot, 1994):

- The diffusion coefficent may be represented by the gas permeability coefficient of the covercrete layer. This is beneficial as air-permeation is more easily measurable by existing measurement techniques, and it also provides opportunities for durability specification and performance-based assessment of built RC structures (Parrot, 1994; Basheer et al., 1996).
- Binding capacity is a function of the calcium oxide content in the cement blend, and the degree of hydration achieved (Parrot, 1994).
- The differences in atmospheric carbon dioxide content are ignored (Parrot, 1994).

- With an increase in relative humidity, the governing relationship deviates from the square root relationship. This is due to the reduction in permeability as a result of water blocking the pores (Parrot, 1994).

Based on these assumptions, Parrott was able to model the diffusion process of carbonation in high relative humidity environments (Richardson, 2002). The total service life of a RC structure is based on the corrosion model developed by Tuutti (1982), as shown in Figure 2.12.

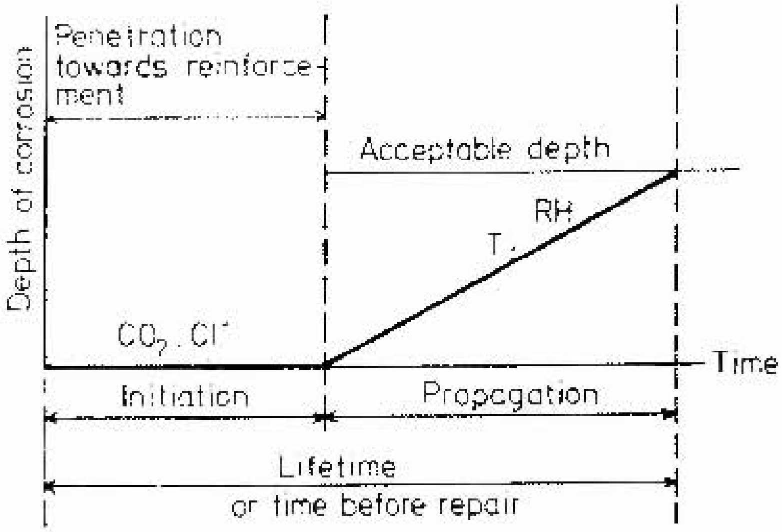


Figure 2.12: Corrosion model for steel reinforcement in concrete (Tuutti, 1982)

The model seperates the total service life of the structure into initiation and propagation stages. It is a significant simplification of the real process, but has been verified by Tuutti as well as other authors (Tuutti, 1982). The total service life is given by Equation 2.18 (Tuutti, 1982):

$$t = t_i + t_p \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.18)$$

where:

t_i = Initiation period (Time required for the carbonation front to reach the steel reinforcement) (years)

t_p = Propagation period (Time during which steel corrosion occurs)

The relationship developed by Parrott describing the initiation period (t_i in Equation 2.18) is given by Equation 2.19 (Parrott, 1994).

$$D = d = \frac{a\,k^{0.4}\,t_i^{\,n}}{c^{0.5}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.19)$$

where:

D = Minimum concrete cover depth (mm)

d = Depth of carbonation at the end of initiation phase (mm)

a = Coefficient (assigned a value of 64 based on extensive literature research by Parrot (1994)) (Richardson, 2002)

k = Air-permeability of the cover concrete (m^2). If k is unknown, it may still be calculated based on permeability of a laboratory representative sample dried at 60% relative humidity (Parrott, 1994).

t_i = Initiation period to start of corrosion (years)

n = Power exponent taken as approximately 0.5 for indoor exposure. However, if relative humidity rises above 70%, the exponent decreases (Parrott, 1994). This takes into account the effect of reduced permeability due to moisture blocking in the pores.

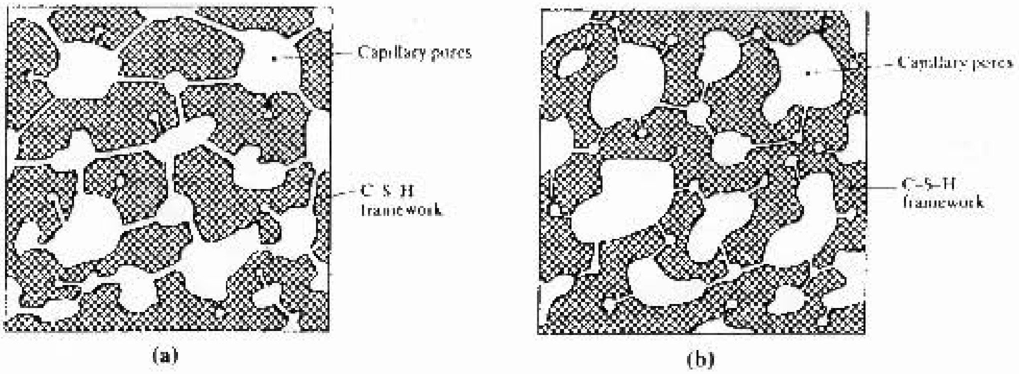
c = Describes the calcium oxide (CaO) content (kg/m^3) in the hydrated concrete cover matrix that acts as reserve alkalinity. This is dependent on cement composition, exposure condition and proportion of reactive cement (Parrott, 1994).

As shown in Equation 2.19, the initiation period is considered complete when the carbonation front has reached the minimum concrete cover depth (Parrott, 1994). The propagation period describes the time taken for visible cracking to occur before the onset of spalling. Another model was proposed by the Comité Euro-International du Béton (CEB), taking into account the chemical buffering effect (Richardson, 2002), and thus providing greater control of the service life model.

The model proposed by Parrot (1994) provides insight into one of the earliest well established service life prediction models for carbonation-induced corrosion. It is, however, important to emphasise the accepted use of gas-permeability for predicting what is fundamentally a diffusion process. One of the key considerations for a permeability-based model is an appropriate means to account for the variable effects of moisture in the concrete.

2.5 Factors affecting the permeability of concrete

The validity of using permeation to model a diffusion-related transport mechanism has been briefly discussed in Section 2.4.3 (Parrott, 1994; Nilsson and Luping, 1995; Richardson, 2002). Permeation and diffusion are related by the internal pore network through which fluids and ions pass (Nilsson and Luping, 1995; Basheer et al., 2001). The pore network may be classified according to its porosity, pore size, pore distribution, and network connectivity (Neville, 1981). Larger voids, such as entrapped and entrained air voids, also have a significant effect on concrete permeability (Mehta and Monteiro, 2006), as they provide large passages for the flow of ions or molecules. A distinction should be made between the permeability and porosity of concrete. Figure 2.13 shows two concretes of similar porosity. However, 2.13(a) may be considerably more permeable than 2.13(b), as the network consists of larger passages and connectivity between the capillary pores (Neville and Brooks, 2010).



(a) (b)

Figure 2.13: Schematic of (a) high and (b) low permeability concretes (Neville and Brooks, 2010)

One of the governing factors of concrete permeability is porosity (Powers, 1958; Neville, 1981; Richardson, 2002; Mehta and Monteiro, 2006). Capillary porosity is largely affected by the cement paste microstructure and degree of hydration (Richardson, 2002; Neville and Brooks, 2010). The relationship between concrete porosity and permeability is shown in Figure 2.14.

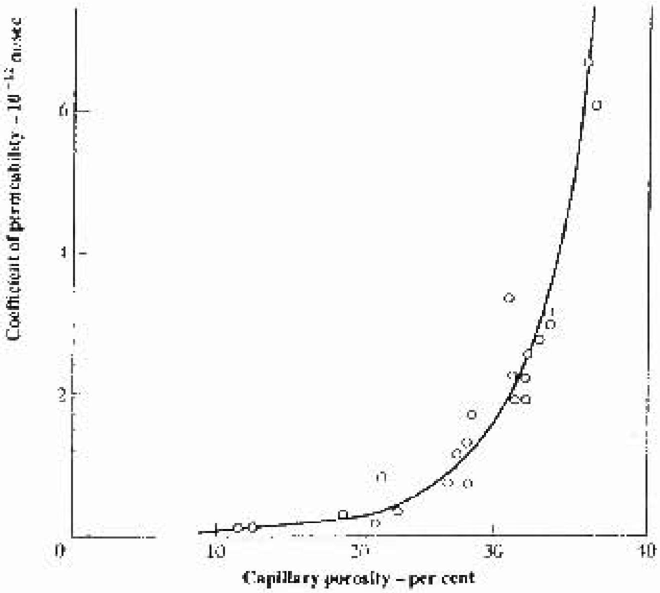


Figure 2.14: Effect of capillary porosity on concrete permeability (Powers, 1958)

According to the South African national standards (SANS), impermeability is identified as "one of the main characteristics that enhances the durability of any concrete" (SANS 10100-2, 1994). The measurement of permeability is useful as it provides an indication of the combined effect of good mix design and construction quality. Means for achieving a lower permeability concrete are also generally well understood (Richardson, 2002). These include a suitably low w/c ratio, good compaction and good curing practice (Richardson, 2002; Mehta and Monteiro, 2006). Developments in concrete test methods have rendered the test for concrete permeability easier to perform, while still ensuring accurate and reproducible results both in the laboratory and in-situ.

It is accepted that permeation may be used for carbonation prediction, provided that the substance phase (viz. liquid, vapour, and gas), substance type (e.g. air, oxygen, and carbon dioxide), concrete moisture condition and temperature are accounted for (Nilsson and Luping, 1995; Ollivier et al., 1995). Since gas permeability is sensitive to both mix design and construction quality, it is important to understand the independent effect of each of these parameters.

A brief description of the key factors affecting the permeability of concrete will be discussed, with particular attention paid to gas permeability.

2.5.1 Concrete mix proportioning

Concrete mix proportioning is the selection of materials and quantities in order to achieve specific concrete requirements. The common concrete mix constituents include (Addis and Goodman, 2009):

- Cement and cement extenders
- Water
- Aggregate (coarse and fine)
- Admixtures (e.g. superplasticizer)
- Fibres

Correct proportioning of the mix constituents is essential to reduce the permeability of a concrete mix. Good mix proportioning must account for many variables and processes, and therefore a completely theoretical approach is not possible. Guidelines for achieving a well-proportioned mix are presented in the **Cement and Concrete Institute (C&CI) Method** (Addis and Goodman, 2009). This method provides certain tools and estimates for achieving a well proportioned mix, however, trial mixes are still required in order to verify the concrete properties (Addis and Goodman, 2009).

Prescriptive mix specifications have been developed in order to improve the durability of structures exposed to various environments (Grieve, 2009). These specifications may be used to provide better estimates for suitable mix proportioning. These recommendations commonly take into account minimum cement content, cement type, w/c ratio, minimum cover depth and strength requirements (Grieve, 2009). However, these guidelines have come into question with more research into performance-based approaches. More information regarding the progression from prescriptive to performance-based approaches is presented in Section 2.8 (Alexander et al., 2008; Ballim et al., 2009).

2.5.2 Cement type and content

The total cement content includes both the primary cement content, as well as cement extender content. The fineness of cement may be described by its Blaine number (m^2/kg), with a higher Blaine number (or specific surface area) being assigned to finer cements (Taylor, 1990). Coarse particles result in a higher porosity cement paste than finer particles (Powers et al., 1954). Finer cement particles also require less time to achieve the same strength, due to their increased surface area and hence increased rate of hydration (Neville and Brooks, 2010).

In South Africa, the most common primary cement is Portland cement (PC), and common cement extenders include GGBS, FA and CSF. Cement extenders are generally waste materials derived from industrial processes, and have the potential to improve the properties of a concrete if used appropriately (Grieve, 2009). Details regarding the properties and influence of these cement extenders (as used in SA) is well documented by Grieve (2009).

A common advantage of these cement extenders is the reduction of concrete permeability when suitably proportioned (Neville, 1981; Grieve, 2009). The following recommendations are made by SANS 50197-1 (2000), for the addition of cement extenders:

- For a PC/GGBS blend: CEM II gives a recommended mass % of 6 to 35%, and CEM III a mass % of 36 to 95%. In South Africa, 50% replacement is commonly used.
- For a PC/FA blend: CEM II gives a recommended mass % of 6 to 35%. In South Africa, 30% replacement is commonly used.
- For a PC/CSF blend: CEM II gives a recommended mass % of 6 to 10%. In South Africa, 10% replacement is commonly used.

While low permeability is beneficial for improving durability (due to the slowing of transport mechanisms at the surface), it is equally important to consider the effect of the cement extenders on the specific deterioration mechanism under consideration. For example, carbonation rate is largely affected by the calcium hydroxide ($Ca(OH)_2$) content produced in the hydration process. The presence of calcium hydroxide increases pore solution pH, and acts as a buffer to slow the carbonation front (see Section 2.4.2). Figure 2.15 shows the effect of PC replacement using (a) Pozzolan and (b) slag cement extenders on calcium hydroxide production.

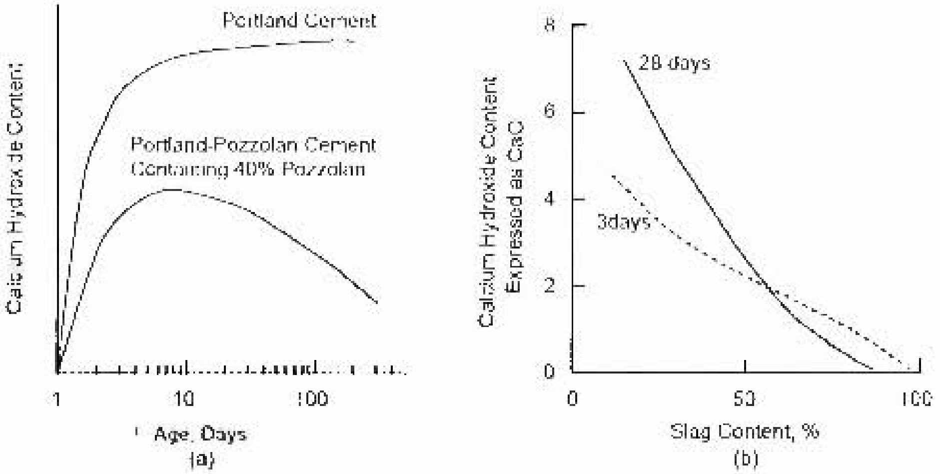


Figure 2.15: Influence of binder type on Ca(OH)$_2$ content (Mehta et al., 2006)

In Figure 2.15(a), the effect of replacement of PC with 40% Pozzolan (e.g. FA) tends to lower the calcium hydroxide produced, and hence results in a more rapid rate of carbonation (Mehta and Monteiro, 2006; Neville, 2011). However, the presence of the FA also results in a denser hardened concrete matrix. The net result is dependent on the percentage replacement, and (very importantly) on the quality of curing performed (Neville, 2011). Figure 2.15(b) shows a similar trend. That is, the reduction of calcium hydroxide production through slag (GGBS) replacement (Neville, 1981). The replacement of PC with slag is generally considered to cause an increase in the carbonation rate (Grieve, 2009). This may be linked to the necessity for curing of GGBS cements. More information on the effect of curing on permeability is given in Section 2.5.6.

2.5.3 Water/cement ratio

The water/cement (w/c) ratio is considered one of the most important parameters for strength development and reduction of concrete permeability. In this case, the cement content refers to a combination of both Portland cement and cement extender. A low w/c ratio leads to high concrete strength and impermeability, provided that the construction practice (such as curing and compaction) is of a high quality (Richardson, 2002; Grieve, 2009; Neville and Brooks, 2010). Figure 2.16 shows that for cement pastes of the same degree of hydration, an increase in w/c ratio results in an increase in concrete permeability (Powers et al., 1954; Ollivier et al., 1995). In particular, it can also be seen that below a w/c ratio of approximately 0.6 pore discontinuity is achieved (Neville and Brooks, 2010). Pore discontinuity will be explained in Section 2.5.6.

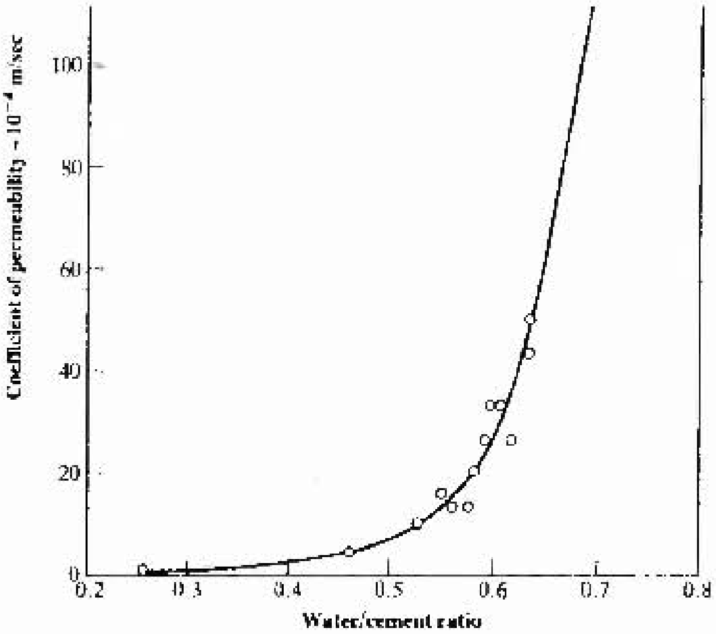


Figure 2.16: Effect of w/c ratio on permeability for mature cement paste (Powers et al., 1954)

A high-strength concrete is usually specified a w/c ratio in the range of 0.25 and 0.40, while that for normal strength concrete may be in the range of 0.45 and 0.70 (Grieve, 2009). Figure 2.16 also shows that for higher permeability concretes (with a w/c ratio above 0.60), the rise in permeability becomes extremely steep (Richardson, 2002). A low w/c ratio is usually achieved at the expense of good workability in the mix. This has led to the increased usage of water-reducing admixtures (such as plasticizers) (Richardson, 2002), which increase workability by dispersion of cement particles in the fresh state, allowing a reduced water content which would otherwise not possible.

In essence, the full potential of a low w/c ratio concrete is only realised if allowed to reach a high degree of hydration. This reveals the importance of curing to achieve good quality and low permeability concretes (Neville, 1981). Figure 2.17 shows the effect of poor curing (which results in a low degree of hydration) on capillary porosity (which governs the cement paste permeability) (Mehta and Monteiro, 2006).

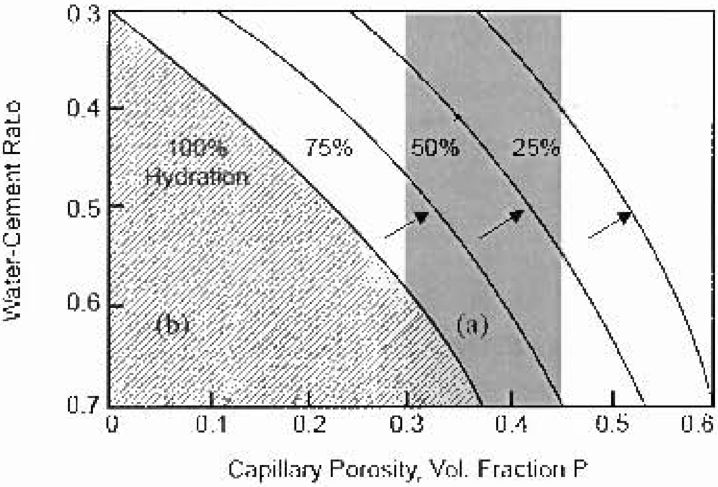


Figure 2.17: Interaction between w/c ratio, curing and capillary porosity (Mehta et al., 2006)

The typical range of capillary porosity in the cement paste is highlighted in Figure 2.17 by shaded area (a). Shaded area (b) is theoretically possible, however, in most cases this will be practically impossible due to preparation techniques employed in practice. In the case of fully hydrated concretes where the w/c ratio is below 0.4, the capillary porosity is close to zero (Grieve, 2009). Unhydrated cement (as a result of poor curing) leaves capillary voids and increases permeability, and the effect of poor curing on capillary space is substantially more severe for higher w/c ratios (Mehta and Monteiro, 2006). It may therefore be concluded that low permeability concrete requires not only a low w/c ratio, but also good quality construction practice. In work performed by Ng'ang'a (2011), it was found that durability (in accordance with specifications for the performance-based DI approach) is not dependent on the strength of concrete. This supports the fact that a low w/c ratio alone cannot ensure a low permeability concrete, but only the potential thereof.

2.5.4 Fine and coarse aggregates

The transport properties in concrete are greatly affected by the presence of aggregates. Aggregate properties may be classified according to size, shape, texture and porosity. Aggregate porosity is usually isolated from the cement paste matrix in a well compacted and cured concrete (Richardson, 2002). However, if the aggregate permeability is considerably lower than that of the cement paste, then increasing aggregate size and content increases tortuosity of the molecular/ionic flow path, and hence indirectly reduces total permeability (Schriver et al., 2004; Alexander et al., 2008). Further, by increasing aggregate content, the effective flow path area is also reduced (Neville, 1981). It should be noted, however, that in research by Mehta and Monteiro (2006), the opposite effect (viz. increasing aggregate content increases permeability) was observed.

Figure 2.18 shows that the addition of aggregates to cement paste increases permeability of the concrete (Mehta and Monteiro, 2006). In addition, it shows that increasing aggregate size also increases concrete permeability. The reason for this discrepancy is not fully understood, but may be attributed to the interaction between ITZ regions, and the possibility of microcracking in the cement paste matrix (Ollivier et al., 1995). This has been discussed in Section 2.2.1.

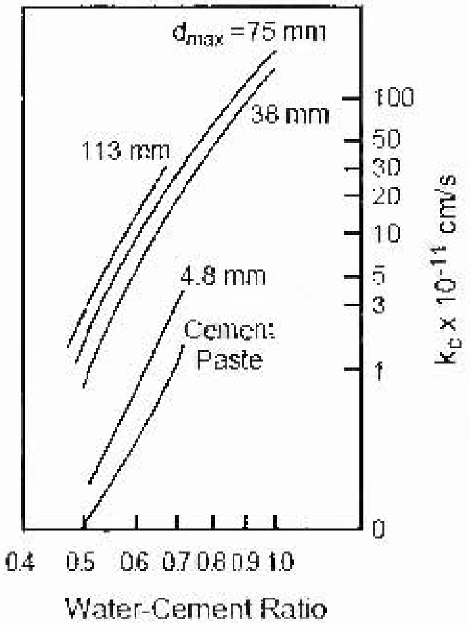


Figure 2.18: Effect of aggregate size and w/c ratio on concrete permeability (Mehta and Monteiro, 2006)

The effect of aggregate content on concrete permeability is usually small (Neville, 1989) in comparison with that of the cement paste properties. For this reason, properties such as degree of hydration and w/c ratio are considered significantly more important for achieving low permeability concretes (Neville, 1981). The overall effect of aggregate size and quantity on concrete permeability is difficult to assess, mainly due the simultaneous altering of multiple concrete properties (Ollivier et al., 1995).

2.5.5 Concrete mixing and compaction

Good mixing practice ensures that the cement grains are allowed sufficient interaction with water molecules and aggregate grains, such that hydration is possible. Hydration is the primary reason for strength gain and reduced permeability in concrete. Poor mixing may result in localised areas of high and low w/c ratio, as well as increased voids and non-homogeneity in the mix. In this way, poor mixing (or insufficient mixing) results in an increased concrete permeability. Poor mixing may also result in reduced workability, which may be misleading if slump is used as an acceptance criterion for construction quality.

Compaction is the process whereby the concrete is vibrated (or agitated) in order to remove entrapped air voids in the fresh state (Kellerman, 2009). Voids in the hardened state act as a 'bridge' between two otherwise segmented capillary networks (Richardson, 2002). Entrapped air voids are common in vertical concrete members such as shear walls (Richardson, 2002). Good compaction results in an increased density of the mix, and hence, increased strength and impermeability.

2.5.6 Curing regime

Curing is achieved by the maintenance of suitable moisture and temperature conditions while the concrete is in its fresh state (Grieve, 2009). This allows a high degree of hydration, and hence an increase in strength and impermeability (Neville, 1981). This improvement may be explained by the increased cement grain volume through hydration, and the effect of pore blocking and segmentation on the pore network (Neville, 1981; Richardson, 2002; Neville and Brooks, 2010).

Figure 2.19 shows the overall effect of hydration on concrete permeability. In particular, it can be seen that as concrete is allowed to age (in the presence of moisture) the permeability decreases (Neville and Brooks, 2010). In practice, curing is often neglected in order to reduce construction and resource time, but this can be detrimental to the hydration processes and durability of a structural member (Ballim et al., 2009; Neville, 2011).

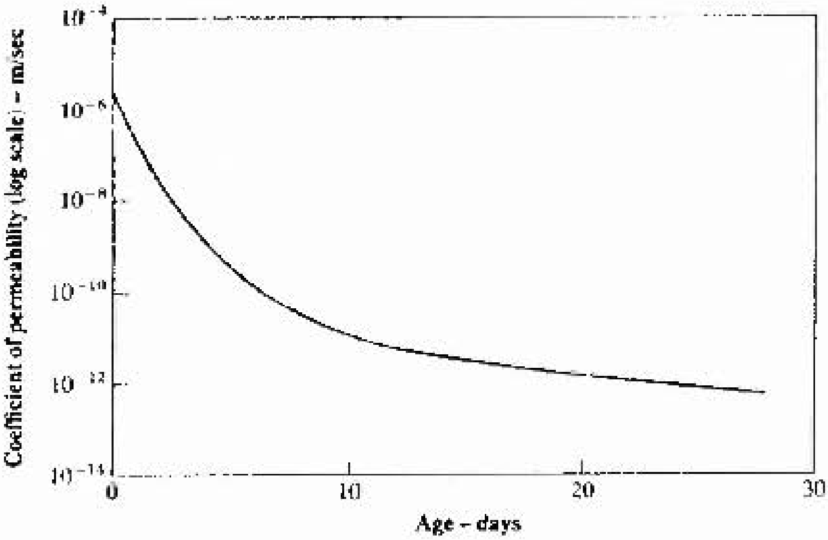


Figure 2.19: Effect of hydration on concrete permeability (Powers et al.,1954)

Segmentation (otherwise referred to as pore discontinuity) is the process whereby gel formation in the passages between capillary pores, prevents permeability between segments of the capillary network, and hence significantly reduces concrete permeability (Neville and Brooks, 2010). The curing time required to achieve segmentation is largely dependent on the w/c ratio (Powers et al., 1959). In particular, it is important to note that for a w/c ratio above 0.5, the curing duration required to achieve segmentation becomes somewhat impractical. Further, a w/c ratio of approximately 0.70 is unlikely to produce a sufficiently impermeable pore network, regardless of the curing duration (Ollivier et al., 1995). This relationship is shown in Table 2.2.

Table 2.2: Minimum curing time for a given w/c ratio in order to achieve segmentation (Powers et al., 1959)

Water/cement ratio by mass	Degree of hydration (%)	Curing period required
0.40	50	3 days
0.45	60	7 days
0.50	70	14 days
0.60	92	6 months
0.70	100	1 year
Over 0.70	100	Impossible

Proper curing is of particular importance for ensuring durability (Ollivier et al., 1995), as it directly affects the permeability of the covercrete layer (Ballim et al., 2009; Grieve, 2009). Reduced permeability in the covercrete layer results in increased resistance to the ingress of deleterious substances (such as carbon dioxide), which affect durability (Kellerman, 2009). With developments in the use of cement extenders to improve durability, the effect of curing on cement extenders is also of particular importance.

The primary cementing reaction is that of PC, however, the reactions of cement extenders such GGBS, FA and CSF are also greatly dependent on the availability of water-filled spaces (Grieve, 2009). These cement extenders slow the rate of hydration, and hence require increased curing time and efficiency in order to achieve good quality concrete (Kellerman, 2009).

A number of curing methods are available to promote the hydration process of concrete. Methods commonly include steam curing, water curing, moisture blocking (e.g. using impermeable plastic) or by the use of chemical curing compounds (Neville, 1981). The selection of curing method is specific to the concrete member type, exposure condition and durability requirements (Ballim et al., 2009).

A higher degree of hydration results in generally improved durability and strength characteristics of concrete. In essence, curing methods usually aim to either provide moisture, or restrict the loss of moisture from the concrete member at early ages. Both types of curing are highly sensitive to ambient temperature, which should be carefully assessed during selection of the curing method (Neville and Brooks, 2010). In addition to the ambient temperature, the type and location of the structural member should also be considered, as some methods may be more suitable than others (Neville and Brooks, 2010).

Wetting of the concrete may be achieved by spraying, misting or ponding of the concrete surface. These are particularly useful for members such as floor slabs, where ponding is easily achieved. Alternatively, applying a saturated layer of sand, hessian or cotton mats, ensures that the concrete has readily available moisture at the surface (Neville and Brooks, 2010). Ponding, if performed correctly, yields significant improvements in terms of strength and durability parameters. Another means of curing is the sealing of the surface using an impermeable membrane such as plastic sheets. This can be implemented at very low cost, with generally good results. An additional benefit of sealing the surface is the suitability to common structural members such as columns and beams. Due to the wide range of curing methods and compounds, only the most common have been mentioned.

2.5.7 Moisture content and temperature

The moisture content in concrete is largely attributed to the exposure conditions at the concrete surface. Increased moisture content inside the concrete pore network, is usually due to wetting/drying cycles, rainfall, or relative humidity in the surrounding atmosphere (Ollivier et al., 1995). An increase in moisture content, results in a decrease in the connectivity of the pore network, and hence a decrease in permeation (Torrent and Fernández Luco, 2007). Further, an increased moisture content is known to have a pore 'blocking' effect on permeability, which results in a reduced gas permeability of concrete (Ollivier et al., 1995; Richardson, 2002; Mehta and Monteiro, 2006; Neville, 2011). The moisture content is also critical for carbonation, as water in the pore network has the ability to block gaseous carbon dioxide flow (Kropp J., 1995), and hence reduce the rate of carbonation. The effect of increasing concrete temperature (assuming identical moisture content) has also been found to reduce permeation, however, this reduction has been found to be small (Ollivier et al., 1995; Torrent and Fernández Luco, 2007). The effect of concrete temperature may be considered a coupled effect (moisture reduction versus microcracking). More on the effects of moisture and temperature on gas-permeability test methods will be discussed in Section 2.7.

2.6 Permeability-based measurement techniques for concrete cover quality

The potential for gas-permeability as a means for quantifying the transport mechanisms in covercrete has been discussed in the preceding sections. This is due to the inherent sensitivity of gas-permeability to changes in mix design (w/c ratio), construction quality (curing), and moisture condition. This has large implications for in-situ assessment of RC structures (Dinku and Reinhardt, 1997; Jacobs, 2006; Ollivier et al, 1995). More recently, a number of new gas-permeability measurement techniques have been investigated (Romer, 2005). These techniques may be classified as either laboratory-based or in-situ test methods. Laboratory-based methods (such as the Cembureau method and OPI test) generally require the extraction of cores from RC structures, after which the specimens are tested under controlled laboratory conditions. In-situ test methods (such as the Autoclam permeability system; Hong Parrot method and Torrent method) are used to measure the permeability of a RC structure in-situ while exposed to the environment.

One of the factors which vary between laboratory-based and in situ test methods for gas-permeation is the gas substance type. The atmosphere (to which a structure is exposed) consists of oxygen, carbon dioxide, water and possibly other harmful chemicals (e.g. chlorides). Carbonation occurs as a result of the reaction between carbon dioxide, moisture and oxygen inside concrete. Laboratory based tests have generally opted for the use of oxygen as the permeating gas, as both carbon dioxide and water result in alteration of the concrete pore structure (Kollek, 1989; Alexander et al., 2008). Some research has been performed investigating the effect of gas type on the permeability of concrete. The gases investigated were commonly oxygen, nitrogen and compressed air (Dinku and Reinhardt, 1997; RILEM TC 116-PCD, 1999; Pilz, 2005). However, due to insufficient literature detailing the effect of gas type, this will not be discussed further.

Extensive work has been performed by the RILEM TC 189-NEC (non-destructive evaluation of the penetrability and thickness of the concrete cover) to compare and assess laboratory-based and in-situ test methods for the transport mechanisms in concrete (Romer, 2005; Andrade et al., 2007; Torrent et al., 2007). This section provides an overview of gas-permeability test methods, with particular emphasis on the OPI test and Torrent method.

2.6.1 Cembureau method

The Cembureau (European Cement Association) method was one of the earliest accepted laboratory-based tests for gas-permeability (Romer, 2005; Ballim et al., 2009). The method consists of passing pure oxygen through a concrete disc (150mm in diameter, 50mm thickness) under a constant pressure, and measuring the resultant flow rate (Kollek, 1989). A schematic of the Cembureau test setup is shown in Figure 2.20.

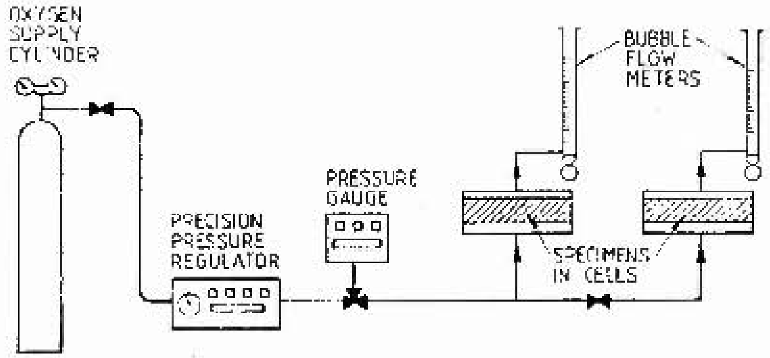


Figure 2.20: Schematic of the Cembureau test method (Kollek, 1989)

The flow rate is measured by means of a volumetric gas flow meter, typically of the soap bubble type (Kollek, 1989). Both laboratory-prepared and in-situ cored specimens may be used, however, suitable preconditioning is required in order to achieve a standard initial moisture condition. Preconditioning permits the comparison of various concrete specimens. In particular, the specimens should be brought to the same moisture condition before testing. This can be achieved through storage of the specimens in a laboratory atmosphere at 20 ± 2°C and 65% relative humidity for 28 days, or alternatively, samples may be dried in a ventilated laboratory environment at 105 ± 5°C and for 7 days followed by 3 days at 20 ± 2°C (Kollek, 1989). This allows comparison of specimens, which would otherwise not be possible because of the pore 'blocking' effect of moisture on gas-permeability measurements (Kollek, 1989).

The Cembureau method has been found reliable and easy to operate, while still achieving good repeatability (Holmes et al., 2009). Further recommendations for the determination of the gas permeability of concrete are given in the RILEM-Cembureau method by RILEM TC 116-PCD (1999) and Carcasses et al. (2002). In particular, the method for preconditioning was investigated, with a number of proposals being made to ensure consistency of the moisture content. These have been found to improve the practicality of the Cembureau test, and also improve test accuracy (Carcasses et al., 2002).

2.6.2 Autoclam permeability system

The Autoclam permeability system is a single chamber method, for the measurement of near surface transport properties (Torrent et al., 2007; Amphora NDT Ltd., 2012). The test is non-destructive, and therefore well suited to the in-situ testing of RC structures (Torrent et al., 2007; Amphora NDT Ltd., 2012). It should be noted, however, that small holes are required in order to mount the bonding ring (Figure 2.21) to the concrete surface (Basheer et al., 2001). The components of the Autoclam permeability system are shown in Figure 2.21.

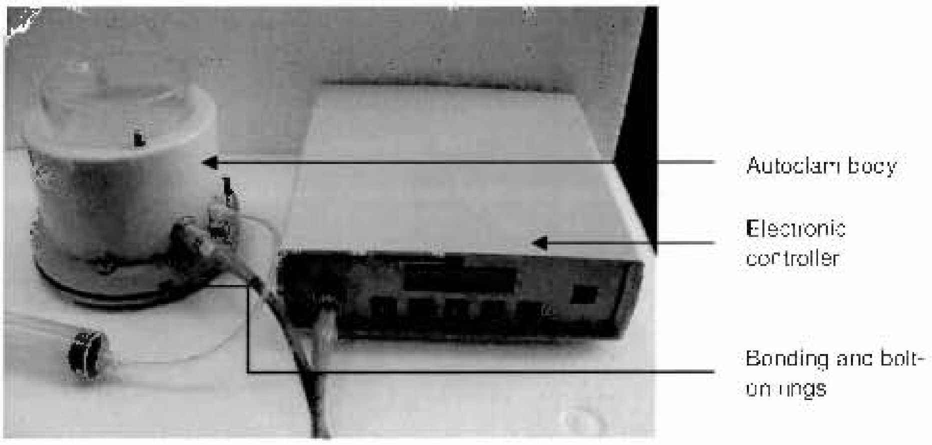


Figure 2.21: Components of the Autoclam permeability system (adapted from Amphora NDT Ltd., 2012)

Depending on the transport mechanism under consideration, the Autoclam may be used to measure air-permeability, water-permeability or water sorptivity of concrete (Basheer et al., 2001; Torrent et al., 2007). In particular, for the air-permeability test, the Autoclam measures the pressure decay after an initial pressure of slightly above 0.5 bars (Holmes et al., 2009). The total test time is 15 minutes, with additional time required for mounting of the bonding ring (Holmes et al., 2009). A schematic of the operation of the Autoclam air-permeability test is shown in Figure 2.22.

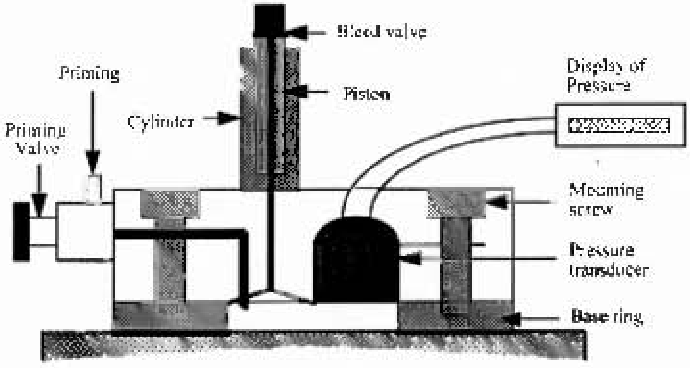


Figure 2.22: Schematic of the operation of the Autoclam air-permeability test (Basheer, 1991)

A good correlation has been found between carbonation depth and gas-permeability (Basheer et al., 2001; Holmes et al., 2009). In addition, research has shown the instrument to produce results with good repeatability and a low degree of scatter (Long et al., 2001; Holmes et al., 2009; Amphora NDT Ltd., 2012). In a comparative test performed by RILEM TC 189-NEC, the correlation between Autoclam permeability system and selected reference tests was found to be weaker than that of similar in-situ test methods (viz. Hong-Parrot method and Torrent methods) (Romer, 2005). It was also found most sensitive to concrete moisture content (which is undesirable for a gas-permeability test), and least capable of differentiating between various covercrete qualities (Romer, 2005).

The effects of temperature and moisture on the Autoclam air-permeability measurement have also been investigated by Basheer and Nolan (2001). The effects of ambient temperature on air-permeability was not found to be significant, however, the effect of increased moisture led to a misleadingly low permeability (Basheer and Nolan, 2001; Long et al., 2001). Since preconditioning is not feasible, guidelines (in terms of insuring the concrete is sufficiently dry before testing) have been proposed by Basheer and Nolan (2001).

The main disadvantage of this test is considered the difficulty associated with achieving a water tight seal between instrument and concrete surface (Long et al., 2001). The test method has been found more suitable to high performance concretes, and concretes with surface treatments, where low permeability measurements are common (Basheer et al., 2001; Amphora NDT Ltd., 2012).

2.6.3 Hong-Parrot method

The Hong-Parrot method is considered an intrusive in-situ test method, as it requires the preparation of a hole approximately 35mm deep (20mm in diameter). At the concrete surface, a steel plug (with an expanding silicone rubber sleeve) is fitted allowing space for a small air-filled cavity (Hong and Parrot, 1989; Parrot, 1991). The pressure transducer and digital indicator are connected to the sealed plug, and act as the source of pressure application to the cavity (Paulmann and Molin, 1995; Torrent et al., 2007). The Hong-Parrot test setup is shown in Figure 2.23.

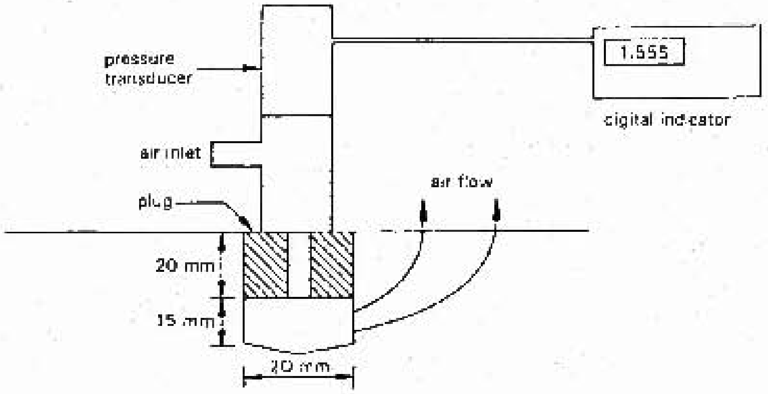


Figure 2.23: Schematic of Hong-Parrot test setup (Hong and Parrot, 1989)

An initial pressure of between 1 and 3 bars is developed inside the cavity (Hong and Parrot, 1989). The covercrete then acts as a pathway for permeation towards the region of low pressure (viz. outside of the concrete element), and hence a pressure decay occurs (Paulmann and Molin, 1995; Torrent et al., 2007). The time taken for a specific pressure drop, typically chosen as 50 to 35 kPa (Parrot, 1991), is recorded (Hong and Parrot, 1989; Parrot, 1991), and evaluated in combination with the influence radius of the air-flow, and humidity inside the cavity (Parrot, 1991).

In order to measure the influence radius of the air-flow, the surrounding concrete is brushed with a soap solution (Parrot, 1991). The radius is then detected by the presence of air bubbles on the concrete surface (Parrot, 1991; Paulmann and Molin, 1995; Torrent et al., 2007). Humidity measurements are taken by means of a humidity probe, which is placed inside the hole one minute after completion of the test (Hong and Parrot, 1989; Parrot, 1991).

2.6.4 Oxygen permeability index test

The oxygen permeability index (OPI) test is a laboratory-based test method for measuring oxygen permeation in concrete (Ballim et al., 2009). It can be used for evaluation of mix specification or for quality control of concrete on site (Alexander et al., 2010).

(i) Sample preparation

Coring of concrete specimens is to be performed between 28 and 35 days after casting. Testing at earlier ages may result misleading permeability results, as insufficent time has been allowed for processes such as hydration to take place (Alexander et al., 2008). It requires the preparation of test specimens (typically circular disks of 70 ± 2mm diameter and 30 ± 2mm thickness) from either laboratory-prepared or site-cored samples (Ballim et al., 2009; Alexander et al., 2010).

(ii) Preconditioning of test specimens

Preconditioning for the OPI test includes the drying of test specimens in an oven (50 ± 2 °C) for approximately 7 days, to achieve minimal moisture content with only a small degree of microstructural alteration. It has been found that drying at higher temperatures (say 150° C) has led to microcracking of the concrete matrix, and hence further increased gas-permeability (Ollivier et al., 2007). The test specimens are then cooled in a dessicator for between 2 and 4 hours. The dessicator allows cooling of the specimens without moisture absorption from the atmosphere. The dimensions of each specimen are then measured using a vernier caliper accurate to within 0.02mm (Alexander et al., 2010).

(iii) Oxygen permeability index test procedure

The test specimens are removed from the dessicator for 30 minutes, and placed inside a (rubber sealed) steel collar. The collar (with concrete specimen inside) is fastened to the top of the pressure cell to ensure no oxygen leaks occur, and thereafter the residual air inside the test chamber and supply pipes is purged. This is performed in order to ensure only oxygen from the supply tank is available for permeation during the test (Alexander et al., 2010). The typical OPI test setup is shown in Figure 2.24.

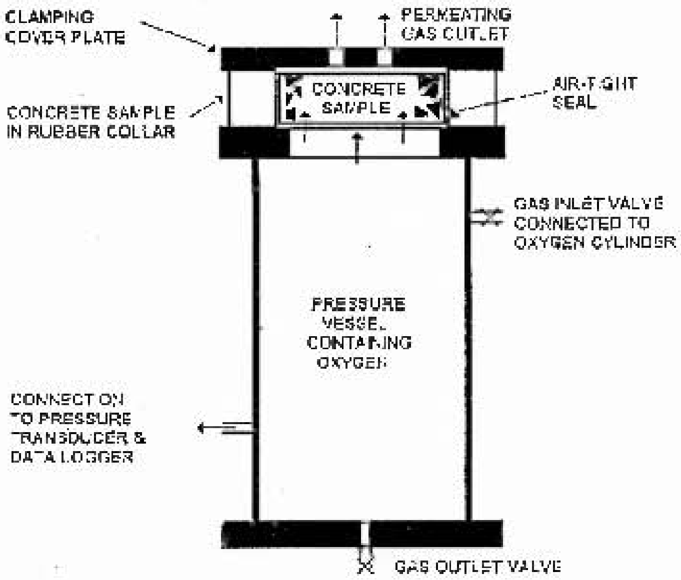


Figure 2.24: Oxygen permeability index test setup (Alexander et al., 2010)

The pressure vessel containing oxygen is pressurised to an initial pressure of 100 ± 5kPa. The pressure decay (due to oxygen passing through the specimen) is then measured automatically. The test may be terminated after 6 hours ± 5 min (or after the pressure has dropped below 50 ± 2 kPa). The pressure decay through the concrete sample is shown in Figure 2.25.

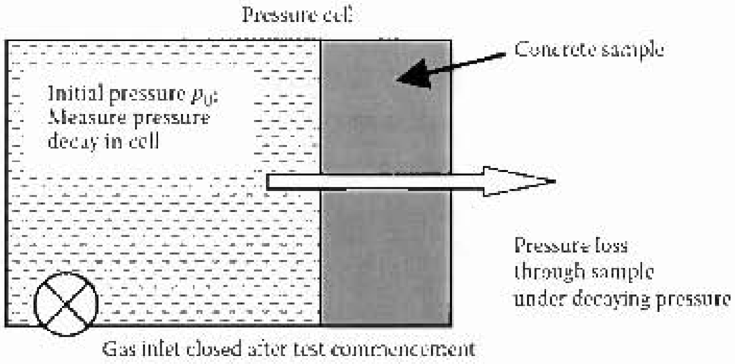


Figure 2.25: Oxygen permeability index test pressure application (Beushausen et al., 2008)

(iv) Data capture and analysis

The pressure decay is measured and stored automatically. The k_{OPI}-value (m/s) is calculated as a regression of the pressure versus time relationship. The fundamental relationship for permeability theory is based on the Darcy Equation (Equation 2.6). The governing relationship for permeability theory (and the OPI test) is shown in Equation 2.20 (Alexander et al., 1999).

$$\frac{\partial m}{\partial t} = \frac{-k.\partial P}{g.\partial z} \quad \text{.......} \quad (2.20)$$

where:

$\frac{\partial m}{\partial t}$ = Rate of mass flow per unit cross-sectional area (kg/s)

$\frac{\partial P}{\partial z}$ = Pressure gradient in the direction of flow (kPa/m)

k = Coefficient of permeability (m/s)

g = Acceleration due to gravity (m/s^2)

By rearranging and making the necessary substitutions, the k_{OPI}-value (m/s) may be calculated by Equation 2.21. The full derivation of this equation is provided by Alexander et al. (1999).

$$k_{OPI} = \frac{\omega V g d}{R A \theta t} . \ln \frac{P_0}{P} \quad \text{.........} \quad (2.21)$$

where: k_{OPI} = k-value for OPI test (m/s)

ω = Molecular mass of permeating gas (kg/mol)

V = Volume of pressure in cylinder (m^3)

g = Acceleration due to gravity (m/s^2)

d = Specimen thickness (m)

R = Universal gas constant (Nm/K.mol)

A = Specimen cross-sectional area (m^2)

θ = Absolute temperature (K)

t = Time (s)

$\frac{P_0}{P}$ = Initial pressure/ pressure at time t (kPa)

The k_{OPI}-value (m/s) is commonly represented as an oxygen permeability index (or OPI). The OPI is given by Equation 2.22 (Alexander et al., 1999).

$$OPI = -\log\ (k_{OPI}) \quad \text{.........} \quad (2.22)$$

where: k_{OPI} = k-value for OPI test (m/s)

The OPI test may be used to assess the as-built quality of a RC structure, as well as for improving the durability-related properties of a concrete mix. It requires at least three valid test results from a particular concrete element (Alexander et al., 2007). For this reason, common practice is for four specimens per structural element to be prepared and tested. The analysis of OPI test results, in accordance with the DI approach, will be described in Section 2.8.1.

2.6.5 Torrent method

The Torrent method is a non-destructive test method for measuring the air-permeability coefficient of concrete (Ballim et al., 2009). It may also be used on laboratory prepared samples, provided the size and preparation of the sample is suitable.

In accordance with Swiss Standard SIA 262/1 (2003), a non-destructive air permeability test method may be used to measure the "impermeability" of concrete, and hence assess the durability related transport mechanisms of the covercrete (Torrent et al., 2012). However, Swiss Standard SIA 262/1 itself provides no limiting values or conformity rules for the Torrent method (Torrent et al., 2012). Subsequently, further research has been performed by the Swiss Federal Highway Administration (ASTRA) in order to prepare a complete and comprehensive recommendation for the air-permeability test procedure. These recommendations were presented by Jacobs et al. (2009) in "Empfehlungen zur Qualitätskontrolle von Beton mit Luftpermeabilitätsmessungen (VSS Report 641)", and serve as a basis for the inclusion of the Torrent method into the Swiss Standard for 2013 (Torrent et al., 2012). It includes recommended air-permeability limiting values, conformity assessment rules and insight into service life prediction based on the Torrent air-permeability coefficient (Torrent et al., 2012).

Currently, there are two commercially available instruments suitable for the Torrent method, namely, the Torrent Permeability Tester (TPT) manufactured by Proceq Switzerland; and the PermeaTORR (P-TORR) manufactured by Materials Advanced Services (M.A.S.) SRL, Argentina (Torrent, 2008). The TPT was the prototype instrument released commercially in 1995 and the P-TORR released in 2009 (Torrent, 2012). However, improvements made in development of the P-TORR have resulted in superior assumptions in theoretical conditions (Torrent, 2012), resulting in more reliable and accurate results as well a decrease in test time (Torrent, 2012). In a comparison of the results from the two instruments it has been found that a good correlation (R = 0.98) does exist (Torrent, 2008). In the discussion to follow, greater attention is paid to the P-TORR instrument, as this instrument will be used in the study which follows.

(i) Preconditioning

Since the test method is primarily for use on-site, preconditioning is not usually possible. However, the influence of moisture, temperature and age on the Torrent method have been extensively researched due to the sensitivity of the test to these factors (Swiss Standard SIA 262/1, 2003; Jacobs, 2005; Jacobs, 2006; Romer and Leemann, 2006; Jacobs, 2007; Jacobs et al., 2009; Torrent and Jacobs, 2009 and Torrent et al., 2012). A detailed discussion on this subject will be presented in Section 2.7.

In accordance with the VSS report 641 prepared by Jacobs et al. (2009), the recommended testing age is between 28 and 90 days. If large amounts of cement extender (such as FA) are used, the minimum testing age should be increased to at least 60 days to ensure sufficient time for hydration and strength development (Jacobs et al., 2009; Denarie et al., 2011; Torrent et al., 2012)

(ii) Torrent method test procedure

In order to perform a meaningful assessment of the structure, the structure should be divided into groups which have the following aspects in common (Jacobs et al., 2009; Torrent et al., 2012):

- Same specified air-permeability coefficient (k_T – value)
- Same concrete type (exposure condition, maximum aggregate size, strength class)
- Same construction practice (placing, compaction, curing)

Each group may consist of a number of structural elements (e.g. beams, slabs, walls and columns). On each structural element, one or more test areas may be selected. The test area may be taken as either one test area per 500m^2, or alternatively one test area per three days of concreting. Essentially, the quantity of test areas is dependent on either the size of a structural element, or the time which was taken for its construction (Jacobs et al., 2009; Torrent et al., 2012). The condition which results in the greater number of test areas should be chosen (Jacobs et al., 2009; Torrent et al., 2012).

Inside each test area 6 random air-permeability measurements are to be taken. The measurement points should be taken sufficiently far from the edge of an element in order to avoid localised areas of poor quality, ensuring more than 200mm from another permeability measurement; and also taken as far as possible from areas with visible defects such as construction joints, cracks and honeycombing (Jacobs et al., 2009; Torrent et al., 2012). An illustration of a suitable test area is shown in Figure 2.26.

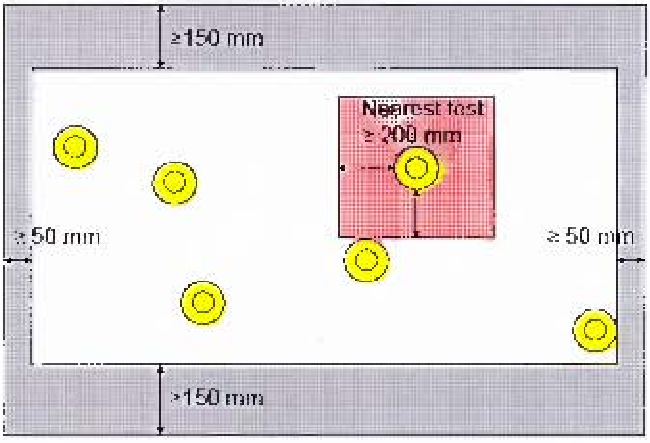


Figure 2.26: Selection of Torrent method measurement points within a test area (Denarie et al., 2011)

After initiation of the test, a negative pressure is developed by means of a vacuum pump and two chamber vacuum cell. The cell is sealed onto the concrete surface under a vacuum pressure (in the outer cell), by means of a pair of soft rubber rings. The pressure regulator maintains an equal pressure in inner and outer chambers, a process which forces the uni-directional air-flow into the concrete member (Ballim et al., 2009; Torrent et al., 2012). The test information is displayed (and can be input) by means of a touchscreen computer, which also permits the download of the results directly to a computer after testing is complete (M.A.S., 2010). The Torrent method test setup is shown in Figure 2.27.

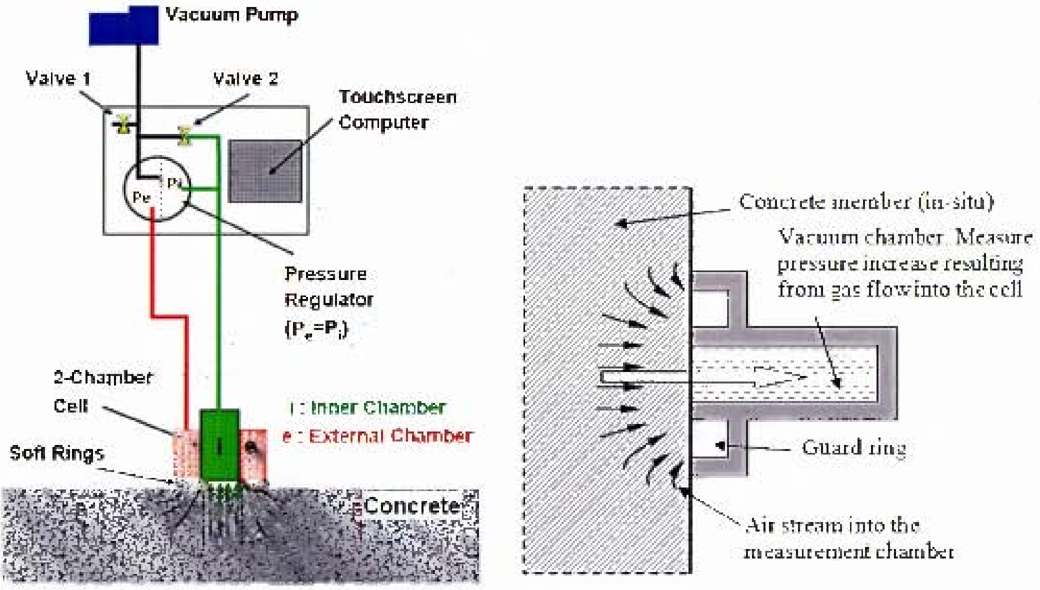


Figure 2.27: (a) Torrent method setup and (b) pressure application (M.A.S., 2010; Beushausen and Alexander, 2008)

(iii) Data capture and analysis

The P-TORR instrument provides a visual display of k_T -value (m^2) at the end of each test, however, each measurement may also be stored to the instrument and downloaded to a computer provided a test is not in progress. A recent improvement to the instrument is the shortening of test duration from 12 to 6 minutes, provided linearity of the pressure development is acceptable (Torrent, 2010; Torrent, 2012).

The equation used by the P-TORR which describes the coefficient of air-permeability is based on the Hagen-Poiseuille law for compressible fluids (see Equation 2.5) (Torrent, 2012). A detailed derivation of Equation 2.23 has been provided by Torrent (2009).

$$k_T = \left(\frac{V_c}{A_c}\right) \cdot \frac{\mu}{2\,\varepsilon\,P_a} \cdot \left[\frac{\ln\left(\frac{P_a + P_f}{P_a - P_f} \cdot \frac{P_a - P_0}{P_a + P_0}\right)}{\sqrt{t_f} - \sqrt{t_0}}\right]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.23)$$

where: k_T – Coefficient of air-permeability (m^2)
V_c = Volume of inner cell system (m^3)
A_c = Cross-sectional area of inner cell (m^2)
μ = Viscosity of air at 20°C (given: $2.0\ 10^{-5}$ N.s/m^2)
ε = Estimated porosity of the covercrete (given: 0.15)

P_a = Atmospheric pressure (N/m^2)

P_f = Pressure in the inner chamber at time t_f (N/m^2)

P_0 = Pressure in the inner chamber at time t_0 (N/m^2)

t_f = Time at the end of test (s)

t_0 = Time at the beginning of the test (given: 60 s) (s)

The Torrent method has been found to give good representative results, which correlate well with other durability test methods (Romer, 2005; Torrent and Jacobs, 2009; Denarie et al., 2011). The aim of the Torrent method (in accordance with Swiss Standard SIA 262/1) is primarily for the control of final covercrete quality, which is affected by both design and construction practice. This allows for early detection of non conformities and increases concrete quality awareness (Jacobs, 2006). The analysis of air-permeability measurements, in accordance with Swiss Standard SIA 262/1 (2003), will be presented in Section 2.8.2.

2.7 Factors affecting gas-permeability measurement techniques

The uncertainties associated with gas-permeability measurement techniques are commonly linked to moisture condition and temperature (Jacobs, 2006). This is more important for non destructive in situ test methods, as preconditioning of the test area is not usually possible. Extensive research by the ASTRA has led to the development of guidelines to account for these factors (Jacobs et al., 2009). These guidelines are intended to complement the current specifications in Swiss Standard SIA 262/1 (2003), and for inclusion into the 2013 Swiss Standards (Torrent et. al., 2012). This section provides a brief summary and explanation of the current recommendations for moisture condition and ambient temperature.

2.7.1 Moisture condition

An increased moisture content generally results in a decrease in the volume and connectivity of the concrete pore network, and hence a decrease in permeability (Torrent and Fernandez Luco, 2007). Further, an increased moisture content is also known to have a pore 'blocking' effect, which results in the reduced gas permeability of concrete (Richardson, 2002; Mehta and Monteiro, 2006; Ollivier et al., 1995; Neville, 2011).

In laboratory-based test methods (such as the OPI test), efforts are made to ensure the concrete is sufficiently dry, such that the gas-permeability results are not misleading. It has been found that drying of test specimens in an oven (50 ± 2°C) for approximately 7 days has the ability to reduce the effects of moisture content without severely altering the concrete microstructure (Alexander et al., 2010). The ability of laboratory-based test methods to eliminate moisture content from other concrete factors is highly desirable (Neville, 2011).

For non destructive in situ test methods such as the Torrent method, moisture content has resulted in much uncertainty with regard to the air-permeability measurement. For this reason, a suitable method is required to either limit or account for the moisture content of in-situ permeability (Paulini, 2010). Swiss Standard SIA 262/1 (2003) states "the concrete cover must be sufficiently dry to avoid interference with the measurement", and that the "moisture (content) of the concrete should be measured at the same place where the air-permeability was tested". Electrical resistivity and humidity measurements are provided as examples of such measures (SIA 262/1, 2003).

According to the VSS report 641 prepared by Jacobs et al. (2009), the following criteria are proposed in order to limit the effects of moisture on the air-permeability measurement (Jacobs et al., 2009; Denarie et al., 2011; Torrent et al., 2012):

1. Using electrical impedance with an instrument such as the concrete encounter instrument (e.g. Tramex CME4 Elcometer), the moisture content (by % mass) should not exceed 5.5%.
2. Using electrical resistivity with a Wenner probe instrument (e.g. Proceq Resipod), the lower limit electrical resistivity values of 10 and 20 kΩ.cm apply to CEM I (viz. PC without reactive mineral additions) and blended cements (e.g. PC with cement extender FA) respectively. If the temperature is not between 15°C and 25°C, an appropriate conversion of electrical resistivity is described.

In order to meet either of these limiting moisture criteria, a minimum of 3-4 weeks after the completion of curing, or alternatively 2-5 days since the last exposure to moisture (e.g. rain, sea-spray, thaw), is recommended. If these conditions are not possible in the structure's natural state, the test area should be covered until such a time as the requirements are met (Jacobs et al., 2009; Denarie et al., 2011; Torrent et al., 2012)

It must be noted that the influence of moisture is not yet completely understood. In an investigation into the effects of moisture on concrete transport properties, Romer (2005) encountered problems with use of the electrical resistivity, and therefore chose to use only electrical impedance. Further, in research performed by Jacobs (2006), an extensive investigation into the influence of concrete type, composition, environment and exposure was performed. Jacobs found that if the concrete is 'very' wet (almost saturated), the evaporation of water led to higher air-permeability measurements than expected (Jacobs, 2006). Further, he concluded that in the case where concrete composition is not known, electrical resistivity may not be a suitable means for establishing moisture content (Jacobs, 2006), possibly due to the effect on various cement extenders on resistivity (Jacobs, 2006). Table 2.3 shows the sensitivity of electrical resistivity to concrete type and storage condition.

Table 2.3: Electrical resistivity for varied of concrete type and storage conditions Extracted from (COST 509, 1997)

Environment	**Expected electrical resistivity values (kΩ.cm)**	
	CEM I concrete	**Concrete containing slag, fly ash, silica fume**
Very wet, submerged, splash zone	5 - 20	< 6.0
Outside, exposed	10 - 40	6.0 - 10.0
Outside, sheltered, coated, hydrophobised, 80 % RH, not carbonated	20 - 50	10.0 - 15.0
Outside, sheltered, coated, hydrophobised, 80 % RH, carbonated	≥ 100	200 - 600+
Indoor climate (50% RH)	≥ 300	400 - 1000+

In an approach presented by Kucharczyková et al. (2010), an equation was developed which corrects the air permeability coefficient based on moisture measurement using the KAKASO capacitive humidity meter. This method will not be presented here, but does provide a forward thinking approach to adjusting the k_T-value for moisture condition (Kucharczyková et al., 2010). Once a greater understanding of the influence of moisture on the Torrent method air-permeability is achieved, it may be expected that the Swiss Standard would include not only limiting moisture content values, but also a means for correcting air-permeability values as a function of moisture content within a specified acceptance region.

2.7.2 Ambient temperature

The effect of increasing ambient concrete temperature has generally been found to reduce the permeability of concrete (Ollivier et al., 1995; Torrent and Fernandez Luco, 2007; Jacobs et al., 2009). The reason for this is not completely understood, however, it may be linked to the expansion of certain concrete constituents, which in turn reduces the spaces for air permeability. This assumes the moisture content is identical for concretes of varied temperature.

For non-destructive in-situ test methods, the ability to control temperature is very difficult. For the Torrent method specifically, Swiss Standard SIA 262/1 (2003) requires only the recording of air temperature during testing. However, more detailed recommendations are provided in the VSS Report 641 by Jacobs et al. (2009). Aside from the effect of temperature on electrical resistivity, a minimum surface temperature (for example, measured by means of an infrared thermometer) of 10°C should be achieved. For more experienced users, measurements with surface temperature between 5 and 10°C are permitted (Jacobs et al., 2009; Denarie et al., 2011; Torrent et al., 2012). In research by Jacobs (2006), it was found that the Torrent method was particularly sensitive to temperature at low permeability values.

2.8 Performance-based approaches for durability specification

It has been recognised that most damage to RC structures is related to poor durability rather than low concrete strength (Richardson, 2002; Torrent and Jacobs, 2009; Torrent et al., 2012). In addition, the monetary implications for structures which deteriorate prematurely (including maintenance and rehabilitation) have become a driving force for the development of guidelines to ensure durability. Originally, the concept of specifying durability was aimed at the development of prescriptive or 'recipe-like' specifications. Prescriptive specifications have primarily relied on limiting w/c ratio and cement content, for ensuring adequate durability performance in a given environment (Hilsdorf, 1995; Alexander et al., 1999; Richardson, 2002; Bentur and Mitchell, 2008; Ballim et al., 2009). This approach has, however, been found lacking as the validity of the approach relies solely on the perceived relationship between mix parameters and the exposure conditions which influence durability (Richardson, 2002; Torrent and Jacobs, 2009).

Subsequently, it has been found that concrete strength does not necessarily link to the transport mechanisms which govern durability (Ng'ang'a et al., 2011). In particular, it has been found that poor construction practice (e.g. compaction and curing) may result in a small reduction in concrete strength, but a considerably larger reduction in durability performance. This significantly reduces the expected service life for a RC structure (Alexander et al., 2008; Bentur and Mitchell, 2008; Torrent et al., 2009). Figure 2.28 shows that if the solid/space ratio lies between 0.55 and 0.70, a small decrease in strength corresponds to a significantly larger increase in concrete permeability.

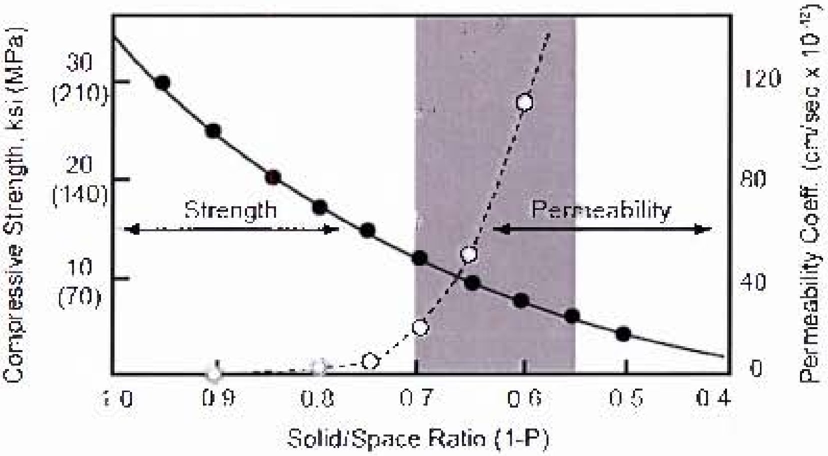


Figure 2.28: Non linearity of relationship between strength and permeability (Mehta et al., 2006)

These prescriptive approaches have also neglected the effect of mix composition and cement extenders on durability-related transport mechanisms (Beushausen et al., 2008; Ballim et al., 2009). A refinement to the prescriptive type approach was presented in European standard EN 206-1, whereby exposure classes were expanded to allow durability design according to a specific deterioration process (Richardson, 2002). This approach was still felt to be insufficient, as it neglected a number of key factors which affect durability, such as construction practice (Richardson, 2002).

The concept of performance-based design and monitoring of structures is quite different to that previously mentioned. In essence, performance-based approaches consider a RC structure in its given environment, and how the structure performs throughout its intended design service life (Ballim et al., 2009). Performance-based factors include w/c ratio, cement type, curing, compaction and construction defects. The cover depth (and accuracy of steelwork) is often measured to compliment the aforementioned performance-based factors, in particular to aid service life prediction. Many of these factors would have not been accounted for by means of a prescriptive-type approach. Emphasis is placed on the most severe deterioration mechanism (based on exposure condition) and the governing factors that affect it. The covercrete layer thickness and its transport properties are deemed critical for the assessment of resistance to the ingress of deleterious substances, and the initiation of steel corrosion.

Performance-based approaches may be used to improve mix design specifications (e.g. mix parameters, curing time); for quality control of the final product after construction; as well as for the prediction of service life (Alexander et al., 1999; Jacobs et al., 2009). Service life prediction models allow the monitoring of a RC structure's durability performance over time. Most service life models require certain input parameters in order to determine the time until corrosion is initiated. Alternatively, given a certain required design service life, deterioration mechanism-specific recommendations, with regard to material type and quantity, can be made.

Service life models take into account the environmental actions taking place on the structure, as well as the structure's ability to resist these actions. Methods differ in that some require testing in addition to input variables, while others only require input variables (Ballim et al., 2009). Some of the common service life prediction models include the European Model "Duracrete"; the North American model " LIFE-365"; the South African approach "Durability Index approach" and the Scandanavian model "Clinconc" (Ballim et al., 2009).

The benefits of performance-based approaches are numerous, and include increased awareness of construction quality; early detection of construction defects and non-conformities; as well as a better understanding of structural behaviour and performance. The DI approach and Swiss approach will be discussed in greater detail.

2.8.1 The South African Durability Index approach

The DI approach was developed by Alexander et al. in the early 1990's as a collaborative research project between the University of Cape Town and the University of Witwatersrand in South Africa (Alexander et al., 1999). The aim of this approach was to address the durability issues in South Africa, through an unambiguous measurement of the covercrete transport properties which govern specific durability-related processes (Alexander et al., 1999; Alexander et al., 2007; Ballim et al., 2009). The DI approach consists of three tests methods, namely, the oxygen permeability index (OPI), chloride conductivity (CC) and water sorptivity (Sorp) tests. In particular, the OPI and CC tests have shown good representativeness for the deterioration caused by carbonation and chloride ingress processes respectively.

In essence, the DI approach aims to characterise the intrinsic potential of concrete to resist various deterioration processes (Alexander et al., 1999). The relationship between indices and durability have great potential for improving design and construction quality. The benefits of this approach include (Alexander et al., 1999):

- Characterisation and specification of an optimised mix design, based on the expected exposure conditions and construction practice.
- Assessment of the quality of concrete on-site, with reference to the quality of site practice (e.g. compaction, curing). This is possible due to the sensitivity of the material indices to these factors.
- Provision of project specific performance-based requirements. These have potential for inclusion into the bill of quantities on the basis of a penalty (or reward) system for durability.
- Prediction of service life in a given environment, based on early-age durability indices. This provides insight into the expected deterioration and maintenance requirements of the RC structure.

A large scale project has been undertaken by the South African National Roads Agency Limited (SANRAL) for implementation of the DI approach. Although the DI approach is adopted in South Africa, the national standards which govern the DI test methods are still under revision (SABS, 2009). It is expected that SANS 516 (parts 1 to 4) will include preparation and testing methodology for each of the test methods listed above (SABS, 2009). For more details regarding the SANRAL implementation of the DI approach (specifically related to the OPI test) see Appendix A (Section 8).

(i) Overview of the durability index test methods

The DI approach consists of three tests methods, namely, the oxygen permeability index (OPI), chloride conductivity (CC) and water sorptivity (Sorp) tests. The OPI test procedure (which links to carbonation) has already been discussed in detail (Section 2.6.4), and therefore will not be discussed further. However, due to the importance of the OPI test in this study, greater detail in the analysis and interpretation of the OPI test results is provided.

The chloride conductivity test is used to measure a concrete specimen's electrical conductivity, which has been related to the chloride ingress experienced by RC structures in a marine environment (Beushausen and Alexander, 2008). It requires the preparation of test specimens (typically circular disks of 70 ± 2mm diameter and 30 ±

2mm thickness) from either laboratory prepared or site-cored samples (Ballim et al., 2009; Alexander et al., 2010). The test specimens are dried in an oven (50 ± 2 °C) and then vacuum saturated for 24 hours in a 5 M sodium chloride (NaCl) solution (Alexander et al., 1999; Ballim et al., 2009). A potential difference is then applied across the test specimen, and the corresponding current measured. The resulting current gives the CC index (ms/cm). Figure 2.29 shows a schematic of the CC test.

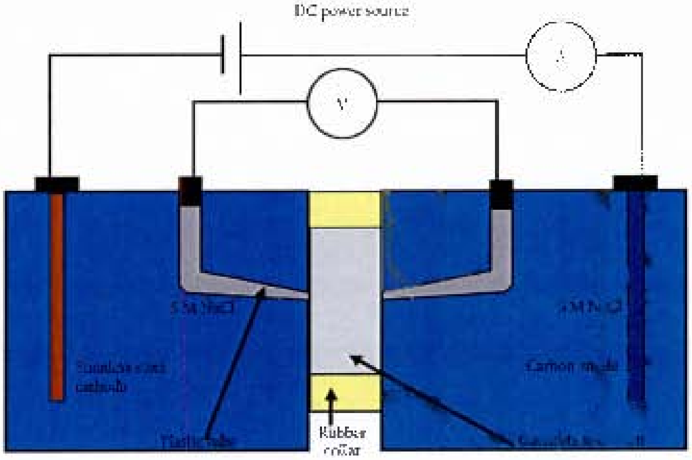


Figure 2.29: Chloride conductivity test setup (Beushausen et al., 2008)

The water sorptivity test is used to measure the capillary absorption properties of the near surface concrete region (Alexander et al., 1999; Beushausen et al., 2008). The test specimens are prepared and dried in the same way as for the OPI test (Alexander et al., 2010). Thereafter, the rounded edge is sealed to ensure uni directional flow, and the sample is placed in a thin layer of water. The sample is weighed incrementally, and then vacuum-saturated. The incremental wetting provides insight into the rate of capillary absorption through the exposed face, and the Sorp index (mm/hr$^{0.5}$) is determined by plotting a straight line of increasing water mass versus the square root of time (Ballim et al., 2009). Figure 2.30 shows an illustration of the water sorptivity test setup.

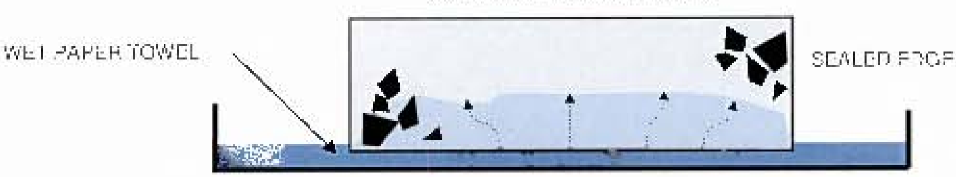


Figure 2.30: Water sorptivity test setup (Adapted from Alexander et al., 1999)

(ii) The OPI test for concrete mix optimization

Isopermeability index curves (Figure 2.31) serve as a guide to assist mix design specification. The cement types OPC, 70/30 PC/FA, 50/50 PC/GGBS and 90/10 PC/CSF are commonly used in South Africa to design for durable RC structures (Alexander et al., 1999). The w/c ratio and curing time are also considered for the specification of a suitable mix design. It is, however, still recommended that trial mixes are performed in order to confirm certain strength or durability properties are achieved (Alexander et al., 1999).

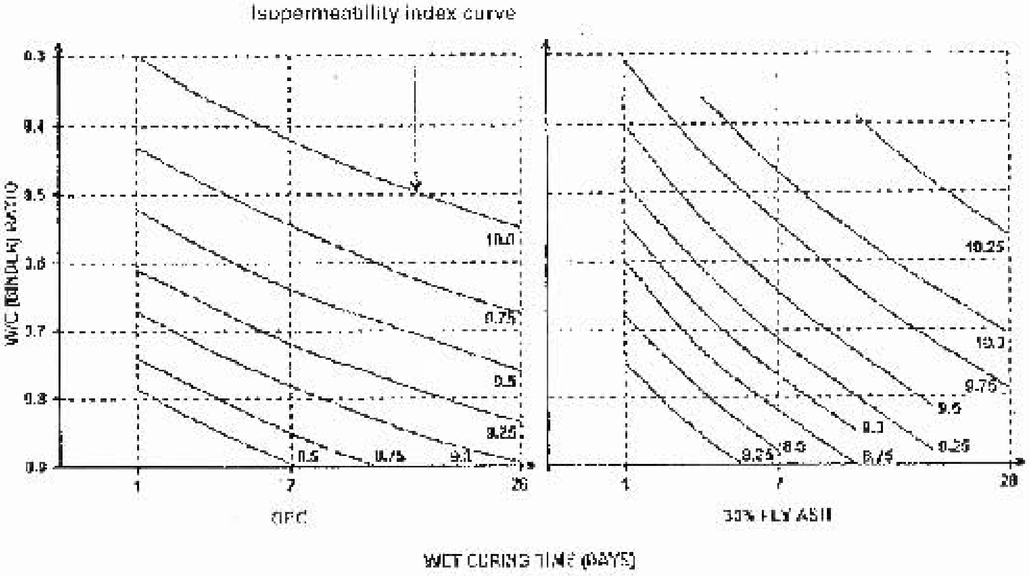


Figure 2.31: Isopermeability curves for varied cement type, w/c ratio and curing time (Alexander et al., 1999)

(iii) The OPI test for performance-based specification

Performance-based specification allows an assessment of the final concrete quality, with respect to certain durability-related transport mechanisms. On this basis, acceptance and rejectance criteria may be developed for a specific project, and a penalty system implemented for non-compliance (Alexander et al., 1999). The ranges for durability classification were presented in Research Monograph 2 by Alexander et al. (1999). These are shown in Table 2.4.

Table 2.4: Commonly accepted limiting Durability Index approach values Extracted from Alexander et al. (2010)

Durability class	**OPI (log scale)**	**Sorptivity (mm/h$^{0.5}$)**	**Conductivity (mS/cm)**
Excellent	> 10	< 6.0	< 0.75
Good	9.5 - 10.0	6.0 - 10.0	0.75 - 1.50
Poor	9.0 - 9.5	10.0 - 15.0	1.50 - 2.50
Very poor	< 9.0	> 15.0	> 2.50

It should be noted that the values presented in Table 2.4 have subsequently become outdated, with continual refinement of these categories since the monograph was prepared. This is shown to provide only a general indication of the expected values for particular concretes.

(iv) The OPI test for carbonation-based service life prediction

Prediction models are required to incorporate a large number parameters and conditions in order to provide a meaningful service life estimate. An early observation of the correlations between OPI and carbonation depth by Alexander et al. (1999), revealed potential of the parameter for long-term durability predictions (Alexander et al., 1999). The correlation between OPI and 4-year carbonation depth is shown in Figure 2.32.

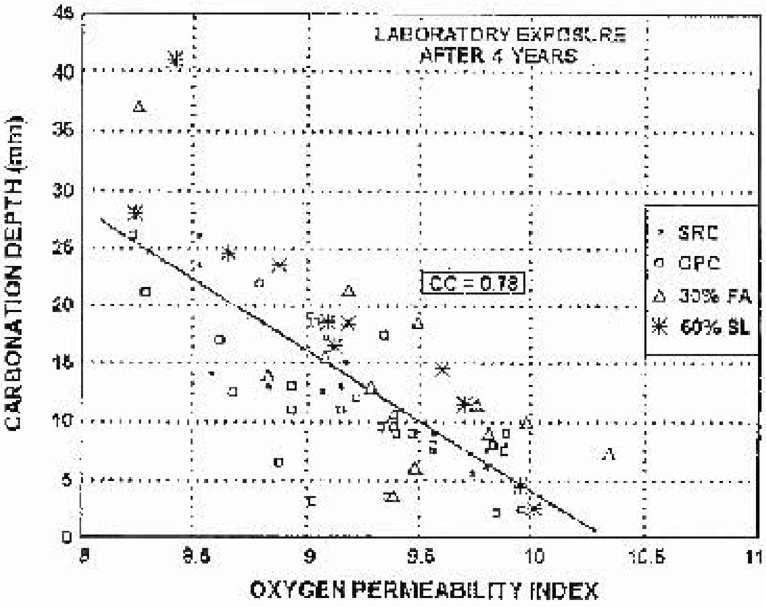


Figure 2.32: Oxygen permeability index versus 4-year carbonation depth (Alexander et al., 1999)

The potential for carbonation-based service life prediction based on the OPI was reported by Mackechnie et al. in 2002. Due to the complexity of this type of prediction, the prediction was limited to the initiation phase of steel-corrosion (see Section 2.4.4). The OPI test results encompassed various cement types, w/c ratios, curing practices and moisture exposure conditions (Mackechnie and Alexander, 2002). The durability prediction was formed empirically, based on the correlation between 28 day oxygen permeability index and 4-year carbonation depth. The relationship between these two variables is shown in Figure 2.33.

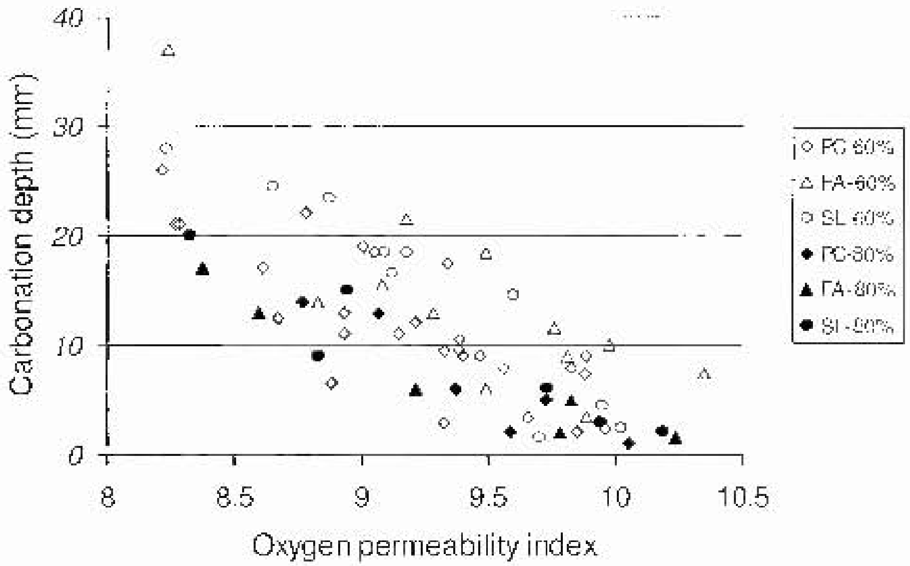


Figure 2.33: 28-day oxygen permeability index versus 4-year carbonation depth (Mackechnie and Alexander, 2002)

As mentioned above, clear distinction should be made between short term (28 day), medium term (1-7 years) and long-term test data (say 50 years) (Mackechnie and Alexander, 2002). For this reason, a suitable model for extrapolating medium term carbonation depth was required. The rate of carbonation agreed well with the general equation for carbonation depth prediction as shown in Equation 2.14 (Ballim et al., 2009). The exposure condition coefficient was taken as 0.4. This is shown in Equation 2.24.

$$x = Dt^{0.4} \qquad (2.24)$$

where: x = Depth of carbonation (mm)
D = Carbonation coefficient (mm/year$^{0.4}$)
t = Time of exposure (years)

Equation 2.24 allowed extrapolation of empirically based medium-term carbonation depth to long-term carbonation depth (Mackechnie and Alexander, 2002). The final prediction model for a 50 year service life is based on exposure condition and oxygen permeability index (Mackechnie and Alexander, 2002). It was also noted that a relative humidity of 65% results in highest rate of carbonation (this is discussed in Section 2.4.2). The 50 year service life prediction model based on 28-day OPI test results is shown in Figure 2.34. It should be noted that the prediction made from Figure 2.34 is independent of binder type.

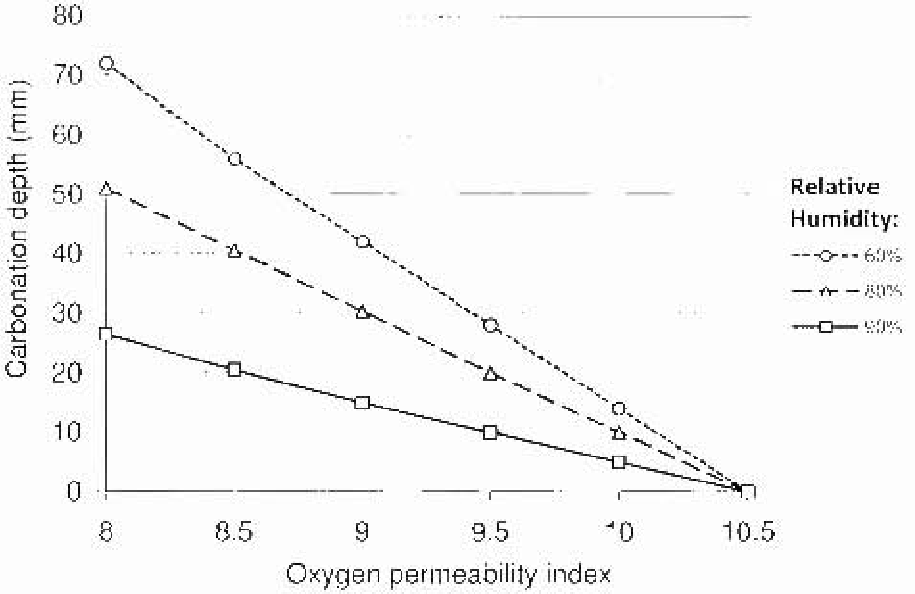


Figure 2.34: Oxygen permeability index based 50-year carbonation depth prediction (Mackechnie and Alexander, 2002)

As described in Section 2.4.3, a study by Salvoldi (2010) presents a more refined means for service life prediction using the OPI test method. As this is yet to be implemented, no further discussion will be presented here. However, the conceptual framework appears to have great potential, provided verification of the model is successful.

(v) *Current practice: Durability indexes for performance-based design and specification of reinforced concrete structures*

Experience and refinement of the DI approach has led to greater understanding and insight into best practice for the approach (Alexander et al., 2008). Best practice currently includes use of the DI approach for both performance-based design and quality control purposes (Beushausen and Alexander, 2009). A framework (Alexander et al., 2008) detailing these concepts has been presented, and serves as the basis for current durability specification and monitoring in South Africa (Beushausen and Alexander, 2009).

In accordance with the FIB model code for service life design (*fib*, 2006), four service life options are provided:

1. Full probabilistic method
2. Partial factor method
3. Deemed-to-satisfy method
4. Avoidance-of-deterioration method

Service life design options 1 to 3 share the requirement for statisitical evaluation of experimental and field data, with varied levels of sophistication (Beushausen and Alexander, 2009). A fully probabilistic approach is regarded the most sophisticated and powerful of the service life options, although the interpretation and outputs are still under debate (Beushausen and Alexander, 2009). The DI approach has generally opted for a deemed-to-satisfy philosophy (Ballim et al., 2009), which is closely comparable to prescriptive type concepts (Beushausen and Alexander, 2009). However, a more 'rigorous' approach has been presented for durability critical structures, or for structures which do not meet the deemed to satisfy conditions (Alexander et al., 2008).

Current prescriptive approaches (most of which are still in use) generally rely on limiting values for w/c ratio, cement content, compressive strength and exposure class (Beushausen and Alexander, 2009). Included in this prescriptive recommendation are guidelines for minimum concrete depth and curing procedure. The problem with this type of approach is twofold (Beushausen and Alexander, 2009):

- In the design phase, the cement type and mineral composition, and its performance in a given environment, is largely ignored.
- Since the quality control is performed on well prepared and cured laboratory samples, the site practice (with regards to pouring, compaction and curing) is not assessed. Further, there is no incentive for contractors to perform good quality construction work, more importantly there is no penalty system for non-compliance.

The DI approach has potential for use in both design and performance-based quality control specification. The performance-based approach for design requires the specification of various performance parameters. These are commonly exposure condition, design service life, materials and desired cover depth. The exposure conditions (specifically that for carbonation-induced corrosion) may be given by the EN 206-1 classes, as shown in Table 2.1.

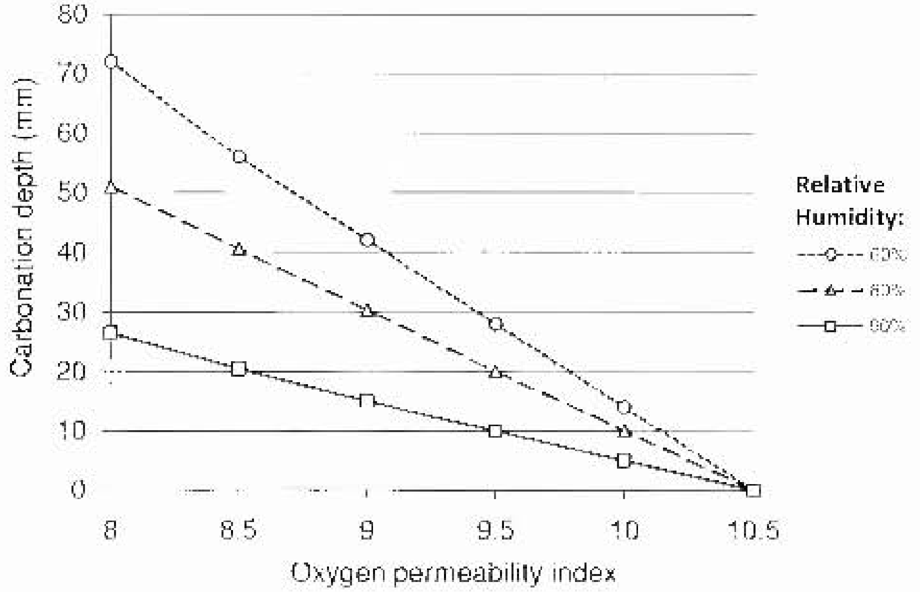


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Table 2.1: Environmental classes for carbonation-induced corrosion (BS EN 206-1, 2000)

2. Corrosion induced by corrosion		
Where concrete containing reinforcement or other embedded metal is exposed to air and moisture, the exposure shall be classified as follows: NOTE The moisture condition relates to that in concrete cover to reinforcement or other embedded metal, but in many cases, conditions in the concrete cover can be taken as reflecting that in the surrounding environment. In these cases classification of the surrounding environment may be adequate. This may not be the case if there is a barrier between concrete and its environment.		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact 'Many' foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

For RC stuctures, the most applicable design service life categories are 50 or 100 years, for common structures and monumental structures respectively (BS EN 1990, 2002; Alexander et al., 2008). A minimum cover depth of 30mm is generally deemed acceptable for resisting carbonation-induced corrosion, however, the final recommendations (for both minimum depth and variability) should be provided by the designer for a specific project (Alexander et al., 2008).

As discussed in Section 2.4.2, for carbonation-induced corrosion to occur, the concrete requires a relative humidity of around 50 to 75% (Neville, 2011). The DI approach therefore recommends a minimum of 30mm cover for exposure classes XC1 and XC2 (very wet/very dry exposure) regardless of the quality of covercrete (Alexander et al., 2008). For exposure classes XC3 and XC4 (where the moisture requirement for carbonation-induced corrosion is met), two deemed-to-satisfy design scenarios are suggested. These generally rely on a compromise between 28-day OPI (rate of carbonation) and minimum cover depth (depth carbonation front is required to penetrate to steelwork). This recommendation is illustrated in Table 2.5.

Table 2.5: Durability index approach framework for reinforced concrete structures (Alexander et al., 2008)

Durability index criteria	Common structures	Monumental structures	
		Case 1	**Case 2**
Service life (years)	50	100	100
Minimum cover (mm)	30	30	40
Minimum OPI	9.7	9.90	9.7

As described above, the DI approach aids specification of certain design parameters, in particular cover depth and minimum OPI value for a given structure type, service life and exposure condition. Further, the approach allows testing of the proposed mix design before construction, such that the individual deterioration processes under consideration may be investigated (Beushausen and Alexander, 2009). In particular, the DI tests may be performed on laboratory-prepared cubes to investigate the combined effect of cement quality, cement type and admixtures on carbonation and chloride ingress resistance, and hence suitable modifications can be made to improve durability performance (Beushausen and Alexander, 2009).

The DI approach has also be used extensively for the performance-based quality control and specification of concrete RC structures (Beushausen and Alexander, 2009). The specified requirements given in Table 2.5 may be evaluated by means of 28-35 day testing of site-derived cores to assess compliance. This provides the designer with an unambiguous criteria for enforcing penalties based on poor construction practice (such as pouring, compaction, and curing) (Alexander et al., 2008). A more 'rigorous' approach has also been outlined within the framework, whereby suitable conformity and acceptance criteria are presented, as well as measures to account for differences in limiting, characteristic and target DI values (Alexander et al., 2008). The authors of the DI approach acknowledge that these DI values are given as 'best estimates', and subject to revision and refinement as greater experience with the approach is established (Alexander et al., 2008).

The South African National Roads Agency Limited (SANRAL) has invested in a large scale implemention of the DI approach to improve the durability of roads and infrastructure in South Africa (Ng'ang'a, 2011). For carbonation-induced corrosion, specifications for exposure classes XC1 to XC4 (and a 100 year design service life) were given. These are summarised in Table 2.6 (SANRAL, 2009).

Table 2.6: SANRAL summary of OPI durability requirements

Exposure class	**OPI_{min} value (four test specimens)**	**OPI_{avg} value (four test specimens)**	**Recommended minimum cover depth (mm)**
XC1	9.0	9.0 - 9.2	40 - 60
XC2	9.0	9.0 - 9.3	40 - 70
XC3	9.0	9.0 - 9.4	40 - 70
XC4	9.0 - 9.2	9.0 - 9.6	40 - 70

Sorptivity requirements were also provided, however, these will not be discussed here. Also presented in the SANRAL specifications were guidelines for reduced payment, as a result of non-compliance in OPI or cover depth measurements (SANRAL, 2009). This is presented as an example of the practical implementation of this approach, and the benefits for designers and clients by means of enforcing performance-based specifications for quality control. Extracts from the SANRAL recommendation are provided in Appendix A (Section 8).

2.8.2 The Swiss approach

Swiss Standard SIA 262/1 - Annex E (2003) presented only the potential for performance-based durability specification using air-permeability measurements. Due to the more recent work of the RILEM TC 189-NEC (Romer, 2005), Jacobs (2006), Torrent and Jacobs (2009), Jacobs et al. (2009), Denarie et al. (2011) and Torrent (2012), it is expected that current recommendations for specifying quality control using air permeability will be adopted by the Swiss Standards for 2013 (Torrent et al., 2012). This approach has been termed by Torrent et al. (2012), the 'The Swiss approach'.

The Torrent method (in accordance with current recommendation by SIA 262/1) has been discussed in detail in Section 2.6.5. Much research has been performed in the last 15 years in order to achieve standardisation of the Torrent method. In this section only the current recommendations (based largely on the work by Jacobs et al. (2009) in "Empfehlungen zur Qualitätskontrolle von Beton mit Luftpermeabilitätsmessungen (VSS Report 641)" will be presented.

(i) The Swiss approach for performance-based specification

Acceptance of the Torrent method has required development in three fundamental areas. The first area of development has been linked to the influence of age, temperature and moisture condition on the air-permeability measurement. This has been discussed in Sections 2.6.5 and 2.7. The other two areas concern the development of limiting values for in-situ testing, and conformity rules for implementation of these limiting values.

In early research by Torrent and Frenzer (1995), a Torrent method air-permeability classification for 28 to 180 day concretes was presented. Subsequently, a good correlation of these criteria with many other durability-related test methods has also been identified (Torrent, 2008; Torrent and Jacobs, 2009). This classification is shown in Table 2.7.

Table 2.7: Classification of the permeability of the concrete cover based on k_T
Extracted from Torrent and Frenzer (1995)

Permeability class	k_T ($10^{-16}m^2$)	Permeability
PK1	< 0.01	Very Low
PK2	0.01 - 0.1	Low
PK3	0.1 - 1.0	Moderate
PK4	1.0 - 10.0	High
PK5	> 10	Very High

Jacobs (2006) performed extensive research into the Torrent method and its practical application. Laboratory work included the testing of five concretes, with varied w/c ratios (0.4-0.6) and cement composition (replacement of PC by FA and CSF cement extenders). A number of conclusions were drawn with regard to each of the areas of uncertainty described above. In particular, both limiting maximum air-permeability values and conformity criteria were presented (Jacobs, 2006). Table 2.8 shows the maximum air-permeability values based on EN 206-1 exposure classes (Table 2.1) and w/c ratio.

Table 2.8: Recommended values for maximum air-permeability
Extracted from Jacobs (2006)

Exposure class	**Maximum w/c- ratio [-]**	**Air permeability (10^{-16} m^2)**	
		Maximum value	**Geometric mean value for $\sigma^* = 0.4$**
XC1, XC2	0.65	1.00	0.40
XC3	0.60	0.60	0.24
XC4, XD1 - XD2, XF1 - XF3	0.50	0.40	0.16
XD3, XF4	0.45	0.20	0.08

The maximum w/c ratio corresponds to the requirements from SN EN 206 - 1: 2000. In addition to the maximum air-permeability values, an approach for conformity control was presented. This is shown in Equation 2.25.

$$\log\left(k_{T\,geometric\,mean}\right) + \sigma^{*} \leq \log\left(k_{T\,maximum\,value}\right) \qquad \text{............} \quad (2.25)$$

where: σ^{*} = Standard deviation (m^2)

$k_{T\,maximum\,value}$ = Maximum air-permeability values (m^2)

This conformity control ensures 85% of air-permeability values (with about 85% probability) lie below the recommended limiting air-permeability value (as given in Table 2.8) (Jacobs, 2006).

The proposal by Jacobs (2006) was followed by recommendations in the VSS Report 641 by Jacobs et al., (2009). In accordance with Swiss Standard 118/262 (Rev 2009), the statistical maximum air-permeability value was given as a function of strength class, exposure condition, cement content and w/c ratio (SIA 118/262, 2009). These recommendations are given in Table 2.9, with EN 206-1 (Table 2.1) exposure classes as before. The k_{Ts} value describes the maximum value for a specified concrete type (Torrent and Jacobs, 2009).

Table 2.9: Limiting air-permeability values in accordance with SIA 118/62 Extracted from Jacobs et al., (2009)

	Concrete types						
	A	B	C	D	E	F	G
Strength class	C25/30	C25/30	C30/37	C25/30	C25/30	C30/37	C30/37
Exposure class (CH)^3	XC1 XC2	XC3	XC4 XF1	XC4 XD1 XF2	XC4 XD1 XF4	XC4 XD3 XF2	XC4 XD3 XF4
Minimum cement [kg/m^3]	280	280	300	300	300	320	320
Maximum w/c ratio	0.65	0.60	0.50	0.50	0.50	0.45	0.45
Recommended k_{Ts} [10^{-16} m^2]		-	2.00	2.00	2.00	0.50	0.50

A refined approach to ensure conformity was presented by Jacobs et al., (2009). In order to satisfy conformity requirements, the following conditions were proposed (Jacobs et al., 2009):

- Condition 1: No more than 1 of 6 required k_{Ti} values may exceed the recommended k_{Ts} value as specified in Table 2.9. In the case where 2 of 6 k_{Ti} values exceed the limiting value, another 6 measurements may to be taken on 6 new points within the same test area (defined in Section 2.6.5).

- Condition 2: For the 6 new measurements within the same test area, no more than 1 of 6 k_{Ti} values may exceed the recommended k_{Ts} value, as specified in Table 2.9.

If conformity is not achieved through conditions 1 or 2, the information may be used for maintenance or remedial work. However, another method may be necessary for conclusive results, such as one of those requiring the extraction of cores (Jacobs et al., 2009). No further recommendations have been made with regards to the choice of test method in the case of failed conformity.

The most recent development in the approach has been presented by Denarie et al. (2011) and Torrent et al. (2012). These approaches are in fact very much the same, and are under review for inclusion into the Swiss Standard for 2013 (Torrent et al., 2012). As shown in Table 2.10 (Denarie et al., 2011; Torrent et al., 2012), the limiting values are given as a function of only exposure classes according to EN 206-1 (Table 2.1).

Table 2.10: Limiting k_{Ts} values as function of exposure condition (Extracted from Denarie et al., 2011)

Exposure	**EN 206 classes**	**k_{Ts} ($10^{-16}m^2$)**
Moderate carbonation	XC1, XC2, XC3	Not required
Severe carbonation **Moderate chlorides** **Moderate frost**	XC4 XD1, XD2a XF1, XF2	2.0
Severe chlorides **Severe frost**	XD2b, XD3 XF3, XF4	0.5

The maximum air permeability values presented by Jacobs (2006) may appear significantly lower than those by SIA 118/262 (2009) and Denarie et al. (2011), however, the basis for conformity assessment has also been altered. This may suggest that with more confidence in the approach, so the maximum values will also be 'relaxed'. It should also be noted that for classes XC1-3, the requirements for air-permeability have been deemed unnecessary, and in effect been removed. This again suggests that with more experience and confidence in the Swiss approach, so the permeability values may be expected to be refined within the given EN 206-1 exposure classes.

(ii) The Swiss approach for carbonation-based service life prediction

As mentioned, in the introduction of this section, most of the available service life prediction models require certain input parameters and conditions in order to provide a remaining service life estimate (Ballim et al., 2009). The Torrent method (with testing performed in accordance with Swiss Standard SIA 262/1), provides some of the necessary input for readily available service life prediction models (e.g. Software Life-365). This input usually includes variables such as the air-permeability coefficient, cover depth and exposure condition. However, according to available literature there appears no preferred model or method for a service life prediction of this form.

2.9 Previous studies supporting integration by permeation measurements

There is much evidence to support the use of gas-permeation as a transport mechanism to model carbonation front ingress, and hence the deterioration caused by carbonation induced corrosion. This insight has led to the development of numerous permeability-based measurement techniques (laboratory-based and in-situ). Further, the limitations of currently adopted prescriptive type approaches have led to the development of performance-based approaches for ensuring concrete durability. The DI approach and Swiss approach are newly established performance-based approaches, both of which show great potential for improving concrete durability in the future (Romer, 2005; Beushausen and Alexander, 2008).

This study is aimed primarily at investigating the factors which affect each of these approaches (specifically for carbonation-induced corrosion); the development of a correlation between OPI and Torrent method (in accordance with SIA 262/1); and opportunities for improvement of the DI approach to include the supplementary use of Torrent method. Previous studies by the RILEM Technical Committee 189-NEC (2005), EMPA (2006) and Wieland (2009) reveal the potential for such an integration, and hence serve as a basis for the study to follow.

2.9.1 RILEM Technical Committee 189-NEC (2005)

The RILEM Technical Committee 189-NEC (for the non-destructive evaluation of the thickness and quality of covercrete) was established in order to evaluate a few commercially available NDT methods, and their sensitivity to various covercrete factors. The NDT methods selected were used to measure the covercrete quality and the depth to the reinforcement, and thereafter compared with similar laboratory-based 'reference' test methods on cored samples (Romer, 2005).

A total of forty slabs, with dimensions 0.3 x 0.9 x 0.12m were cast. Ten different test conditions were considered, each test condition comprising of four panels. In an international comparison of the DI tests, Beushausen et al. (2008) compared the OPI with Torrent air-permeability coefficient for test conditions 1 to 6 (performed within the comparative test). The test conditions selected in the international comparison are shown in Table 2.11.

Table 2.11: Test conditions for the international comparison by RILEM TC 189-NEC (Romer, 2005; Beushausen and Alexander, 2008)

Panel	**1**	**2**	**3**	**4**	**5**	**6**
w/c ratio	0.4	0.55	0.6	0.4	0.55	0.55
Cement type	OPC	OPC	OPC	OPC/Slag	OPC/Slag	OPC/Slag
Moist curing (d)	7					1
Fcu cube (28 d) MPa MPa	62.7	48.5	34.4	52.4	38.2	12.7

Findings from the comparative test included good differentiation capability of Torrent method in comparison with selected reference tests (Romer, 2005). Beushausen and Alexander (2008) found both the OPI test and Torrent method showed a 'highly significant' discrimination of various concretes. The Torrent method did, however, show no significant discrimination for the slag (BFSC) cement types in test conditions 4 and 5 (Romer, 2005; Beushausen and Alexander, 2008). The correlation between OPI k-value and Torrent air-permeability k-value for test conditions 1 to 6 is shown in Figure 2.35.

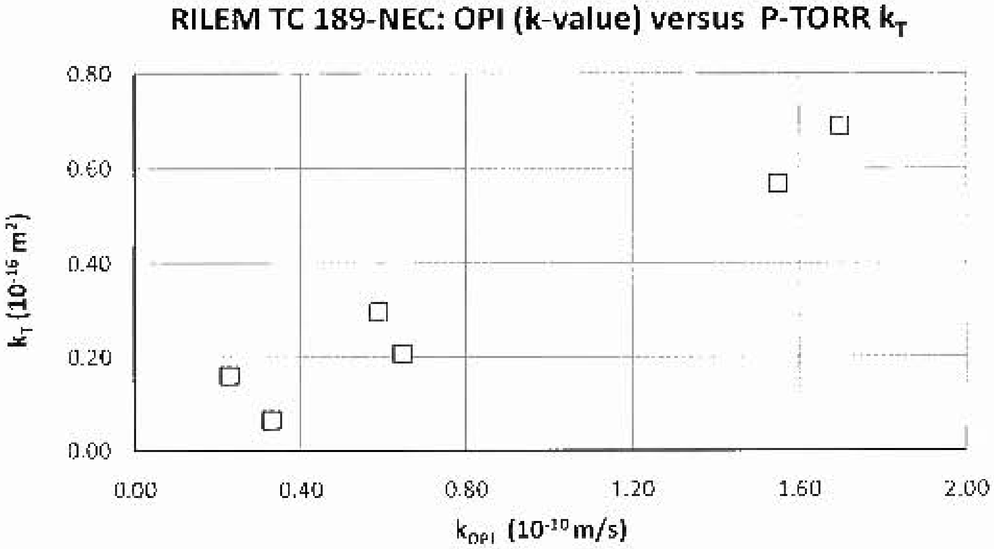


Figure 2.35: RILEM TC: k_{OPI} (m/s) versus k_T (m^2)
Extracted from Beushausen and Alexander (2008)

The testing by RILEM was performed using the commercially available Torrent Permeability Tester (TPT) by Proceq, Switzerland. A small adjustment was required to convert between TPT and P TORR instruments. The adjustment is presented by Torrent (2008) and Torrent (2012), based on 142 air-permeability tests using both instruments on the same concrete samples. The correlation between OPI k-value and Torrent air-permeability k value in Figure 2.35 shows a good, near-linear trend. It should be noted that these values predict very low permeability concretes by both test methods, well below limiting criteria deemed suitable for carbonation-induced corrosion. The correlation also shows clear distinction between varied w/c ratio, and curing time (Romer, 2005; Beushausen and Alexander, 2008).

2.9.2 EMPA (2006)

The aim of this research by Eidgenössische Materialprüfungs - und Forschungsanstalt (2006) (otherwise known as EMPA) was to compare results from various test methods on different concrete samples. More specifically, three gas-permeability test methods were selected. These were the non-destructive Torrent method, and laboratory-based (or semi-invasive) OPI and Cembureau test methods (Romer and Leemann, 2006). It was highlighted that the cross-sectional area and flow geometry of the Torrent method and OPI test is somewhat different. In particular, the sample volume of the OPI test is 1.8 times that of the Torrent method, and the flow is not perfectly uni-directional (as is the case for the OPI test) (Romer and Leemann, 2006). This is important, as it may be responsible for some of the variation between results. A comparison between OPI and Torrent method flow geometry is illustrated in Figure 2.36.

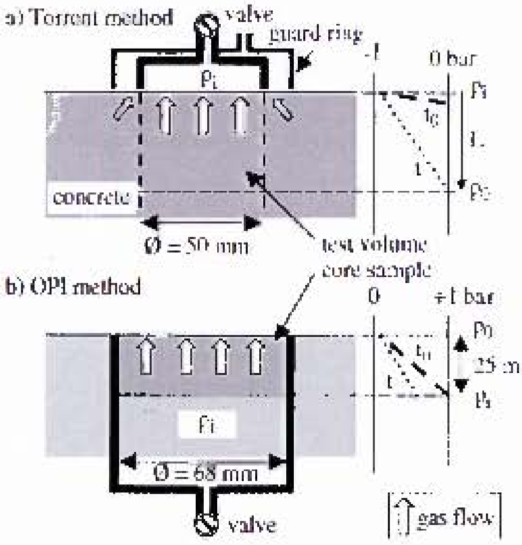


Figure 2.36: Gas flow and cross-sectional area for Torrent method and OPI test (Romer and Leemann 2006)

Six concrete compositions (two 200mm cubes per condition) were produced. For strength identical 150mm cubes were prepared. Four sides of each 200mm cube were sealed (in order to simulate a wall section) after 48 hours. Concrete samples were placed in three controlled environments, of relative humidity 35%, 70% and 90% respectively. The mix composition test conditions M1-M6 are shown in Table 2.12.

Table 2.12: Mix specification and concrete properties for EMPA study (Romer and Leemann, 2006)

Concrete Mix		M1	M2	M3	M4	M5	M6
w/c ratio	-	0.35	0.45	0.40	0.48	0.62	0.48
Cement	kg/m³	* 380	* 300	* 325	** 300	* 275	* 300
Aggregate	kg/m³	1898	1921	1909	1960	1963	1921
Water	kg/m³	133	145	130	145	171	145
Air voids	%	2.8	1.7	3.2	1.5	2.0	5.2
$f_{cm(28)}$	MPa	55.3	47.4	48.1	44.4	35.0	31.2
$f_{cm(90)}$	MPa	62.6	51.8	53.9	45.2	38.3	34.5

* CEM I 42.5

** CEM II A-L 32.5

The testing by EMPA was performed using the commercially available Torrent Permeability Tester (TPT), and hence an adjustment performed to convert to equivalent P-TORR result (Torrent, 2008). Findings from this study showed a compatible sensitivity of the Torrent method with other laboratory-based methods. Further, the Torrent method showed good sensitivity by differentiation between varied concrete strengths and curing conditions (Romer and Leemann, 2006). Figure 2.37 shows a comparison of Torrent air-permeability k-value (m^2) with OPI value.

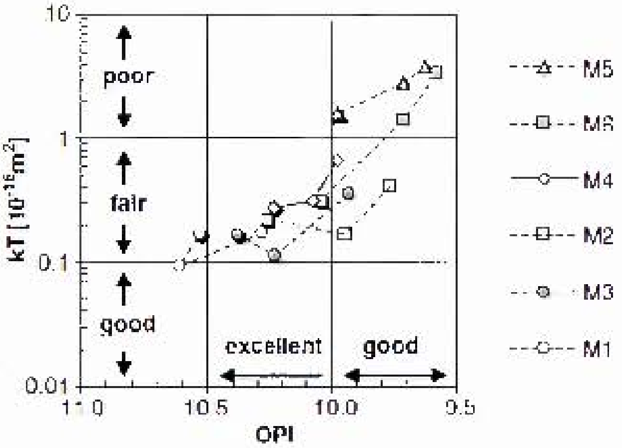


Figure 2.37: EMPA: OPI (-) value versus Torrent air-permeability value (m^2) (Romer and Leemann, 2006)

Figure 2.37 reveals a slight disparity between permeability classes for OPI and Torrent methods. In particular, current classification of permeability results according to the Torrent method (in comparison with the OPI test), may suggest a more 'pessimistic' outcome of the concrete durability (Romer and Leemann, 2006). The correlation between OPI k-value and Torrent air-permeability k-value is shown in Figure 2.38.

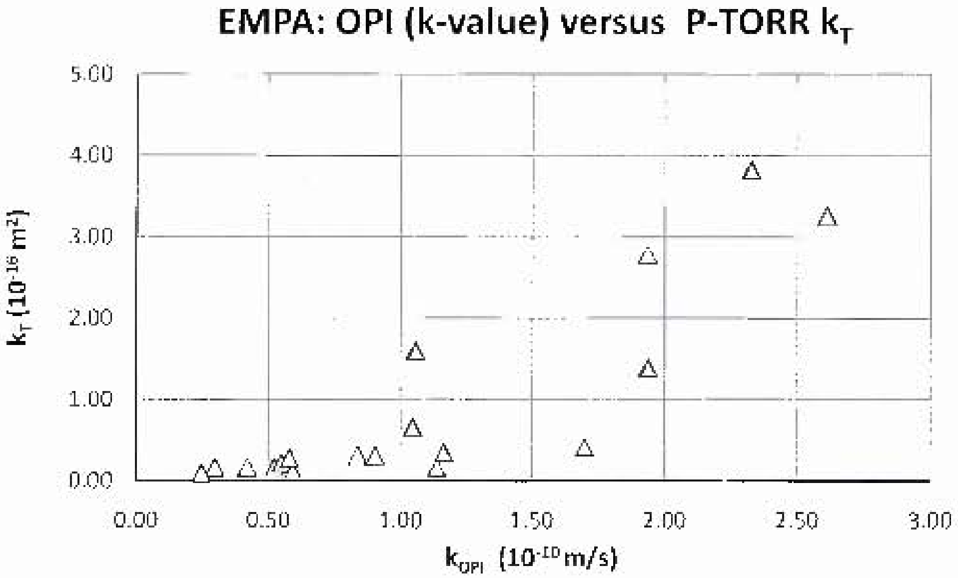


Figure 2.38: EMPA: k_{OPI} (m/s) versus k_T (m^2)
Data courtesy of Romer and Leemann (2006)

Figure 2.38 shows a good correlation between the OPI k-value and Torrent air-permeability k-value. It appears that the relative data scatter remains constant as the permeability increases, which is expected for testing of this nature. Based on the permeability results, it can be seen that the results are considerably higher than that of the work performed by RILEM TC 189-NEC (Beushausen et al., 2008; Romer and Leemann, 2006). This is particularly interesting as the w/c ratio and cement types were quite similar, however, the testing procedure by Romer and Leemann (2006) was quite unique (with regards to preparation, storage (35%, 70% and 90% RH), and testing method) as opposed to the more conventional approach adopted by RILEM TC 189-NEC (Romer and Leemann, 2006).

2.9.3 Wieland (2009)

The study performed by Wieland (2009) was aimed at an investigation into the current prescriptive and performance-based approaches adopted by a number of international standards. These standards included the SANS, Eurocode (with various national annexes), German code as well as the Swiss Standards. More specifically, the research objectives were to highlight how conservative (or otherwise) prescriptive approaches are, when compared with accepted performance-based durability test methods (such as the DI approach) (Wieland, 2009).

The experimental program included 16 different test conditions according to the prescriptive durability requirement of the Eurocode (BS EN 206-2, 2000). Test variables included w/c ratio (0.35 - 0.50), cement type (cement extenders FA, CSF and GGBS) and testing age (28 and 90 days). Concrete specimens were tested for permeability characteristics using the OPI test and Torrent method (Wieland, 2009). The correlation between OPI k-value and Torrent air-permeability k-value is shown in Figure 2.39.

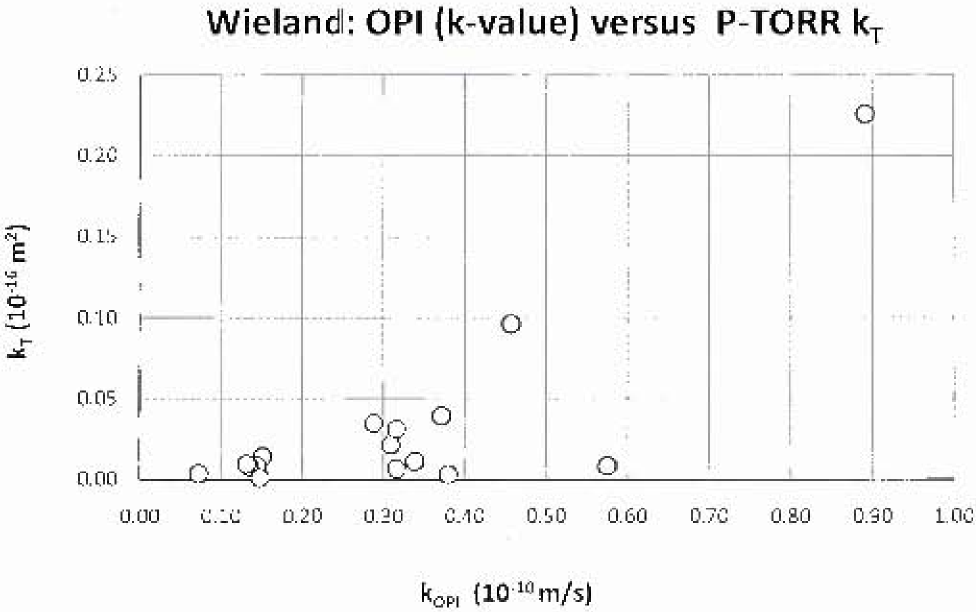


Figure 2.39: Wieland: k_{OPI} (m/s) versus k_T (m^2)
Adapted from Wieland (2009)

From Figure 2.39 it may be concluded that the correlation between gas-permeability values from the two approaches is not particularly good. However, it should be noted that these permeability values (by both methods) suggest very low permeability. This signifies a very impermeable concrete. In a quantitative analysis of this correlation, the permeability is considerably lower than even the strictest specifications by both approaches. In this way, the Torrent method and DI approach would lead to similar conclusions regarding the permeability (and durability) of the concrete (Wieland, 2009).

2.9.4 Compilation of previous studies

Previous studies by the RILEM Technical Committee 189-NEC (2005), EMPA (2006) and Wieland (2009) serve as a basis for the research to follow. The following preliminary conclusions may be drawn:

- The results reveal good sensitivity by both the OPI test and Torrent method to variations in concrete preparation and mix specification.
- The current classification criteria for OPI test and Torrent method are generally compatible, however, results according to the Torrent method suggest a slightly more 'pessimistic' outcome for durability performance.
- Both OPI test and Torrent method draw similar conclusions with regards to the quality of concrete tested (as well as with other durability-related test methods).

Figure 2.40 shows a compilation of research presented above. This relationship will be addressed in more detail in the sections to follow.

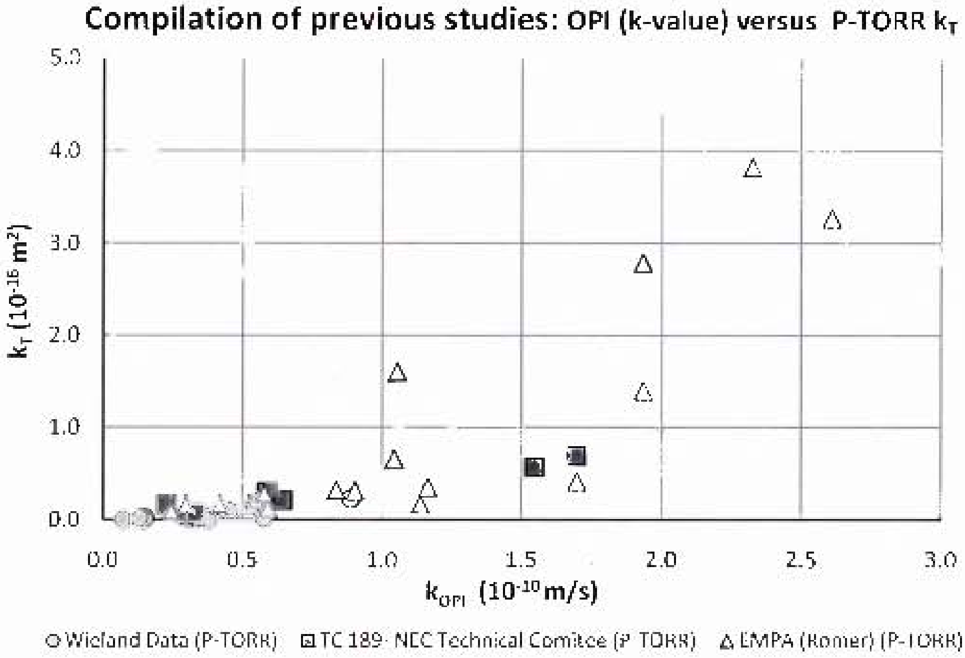


Figure 2.40: Compilation of RILEM, EMPA and Wieland test data

2.10 Summary of literature review

In past years, the durability of many RC structures has been found inadequate, with structures undergoing premature deterioration due to poor durability-based design and construction practice. Research has shown the ability to model various deterioration mechanisms by testing specific transport properties in the near-surface 'covercrete' region. In particular, gas-permeation has been deemed a valid mechanism for modelling carbonation-induced steel corrosion, which is fundamentally a diffusion process.

Carbonation is the process whereby the ingress of carbon dioxide (CO_2) in the form of a carbonation 'front', results in a region of lowered alkalinity in the pore structure. The pH is lowered from approximately 12.0 to below 8.0, at which point the ferric oxide film (maghemite, γ - Fe_2O_3) begins to break down. Steel corrosion then initiates, provided the pore environment has sufficient oxygen (O_2) and moisture (H_2O) to allow corrosion propagation.

The relationship between diffusion and permeation is dependent on the substance type (viz. ion or molecule), substance phase (viz. gas, vapour or liquid) and moisture content inside the pore network. The use of gas-permeation to model carbonation (which is effectively a diffusion process) has a number of advantages for the testing of concrete. One of the key advantages is the sensitivity of permeation to both mix design and construction practice. Mix design factors include cement type and content, w/c ratio and aggregate size. Construction factors commonly include mixing, pouring, compaction and the curing time. Other advantages include the range of commercially available permeability-based instruments, and the reduced test time in comparison with diffusion-related test methods.

Common permeability-based measurement techniques may be classified as either laboratory-based or in-situ NDT methods. Common methods (as presented by the RILEM TC 189-NEC) include the Cembureau method; Autoclam permeability system; Hong-Parrot method; OPI test and Torrent method. Both OPI test and Torrent method have shown a high level of discrimination between mix design and construction-related properties. Measures have been put in place to limit the effect of moisture condition on these test methods, and avoid the 'pore-blocking' effect of moisture on gas-permeability in concrete. These measures (for the Torrent method) may be summarised as follows (Jacobs et al., 2009; Denarie et al., 2011; Torrent et al., 2012):

1. Using electrical impedance with an instrument such as the concrete encounter instrument (e.g. Tramex CME4 Elcometer), the moisture content (by % mass) should not exceed 5.5%.
2. Using electrical resistivity with a Wenner probe instrument (e.g. Proceq Resipod), the lower limit electrical resistivity values of 10 and 20 kΩ.cm apply to CEM I (viz. PC without reactive mineral additions) and blended cements (e.g. PC with cement extender FA) respectively. If the temperature is not between 15°C and 25°C, an appropriate conversion of electrical resistivity is described.

Recent developments in understanding and experience have led to the progression from prescriptive (or 'recipe-like') specifications to performance-based specifications for durability. Prescriptive specifications have primarily relied on limiting w/c ratio and cement content, and thereby ensuring adequate durability performance in a given environment. This type of approach has largely ignored the effects of mineral composition in concrete, as well as construction practice (e.g. compaction and curing).

The DI approach and Swiss approach are performance based approaches which have shown good potential, for improving durability-related design and construction practice. The DI approach (with specific reference to the OPI test) requires the preparation of test specimens (typically circular disks of 70 ± 2mm diameter and 30 ± 2mm thickness) from either laboratory-prepared or site-cored samples. These test specimens are preconditioned to reduce the effects of moisture, and then tested by means of a falling-head permeator setup. The Swiss approach (viz. the use of the Torrent method in accordance with Swiss Standard SIA 262/1), is a non-destructive in-situ test method. The test is performed by means of a portable two-chamber vacuum cell, which (by means of a 'suction' pressure) provides a measure of the air-permeability of the covercrete. A great deal of research has been performed in order to investigate the effect of moisture (and its 'pore blocking' effect) on the Torrent method.

Previous studies by the RILEM TC 189-NEC (2005), EMPA (2006) and Wieland (2009) show a good relationship between results from the OPI test and Torrent method. On this basis, the validity of further research into the integration of these two approaches is concluded.

The next chapter will provide the experimental details and methods used in this study.

CHAPTER 3

3 EXPERIMENTAL PROGRAMME

3.1 Introduction

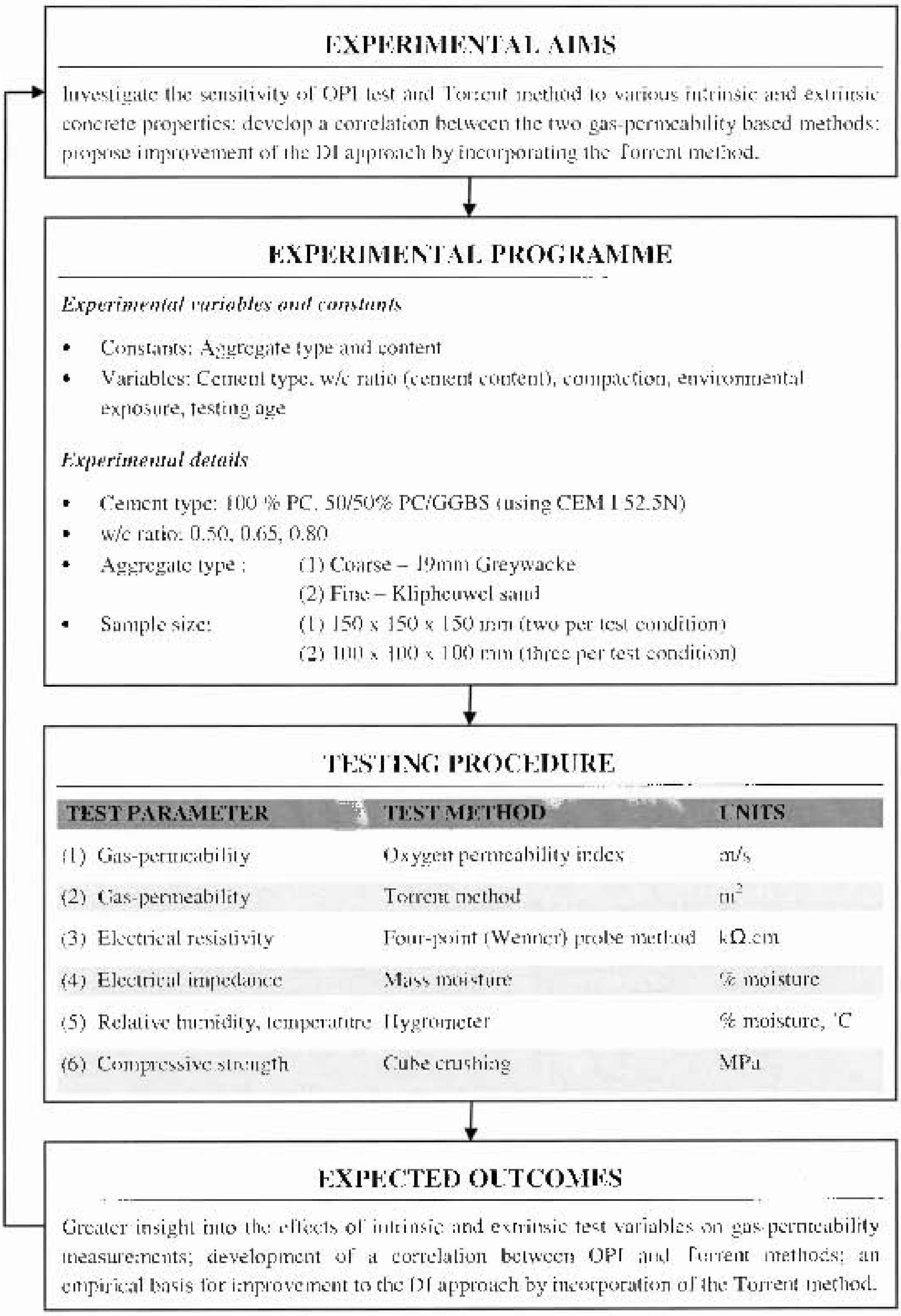
This chapter presents the details for experimental work performed in this study. In particular, the experimental design, specimen preparation and testing details are provided.

The experimental programme was developed in order to quantify the sensitivity of the oxygen permeability index (OPI) test and Torrent method to both intrinsic (w/c ratio, binder type, cement type) and extrinsic (curing, compaction) concrete properties. Commonly used concretes (as found in industry) were prepared, in order to investigate practical implementation of the integrated approach. The integration of gas-permeability test methods is based on the compatibility of these two permeability-based test methods, and the expected correlation between the two permeability coefficients (Section 2.9). The experimental programme was also designed to provide further insight into the effects of moisture on the Torrent method (Section 2.7).

Based on the results by previous authors (Section 2.9), the following key experimental guidelines were identified:

- The test specimens should simulate a common structural element (such as a wall or beam section), which would commonly be tested on-site.
- The concretes should resemble common mixes used by industry for durability-critical structures, with specific reference to cement type and w/c ratio specification.
- Previous studies have investigated particularly low-permeability concretes. For this reason, a wide range of permeability data (from low to high permeability) is desirable, to determine whether the trend developed by previous studies (for low permeability's) may be extrapolated to achieve a more generalised correlation.
- In addition to intrinsic variables (w/c ratio, binder type, cement type), the sensitivity of OPI test and Torrent method to extrinsic factors (environmental exposure, compaction) should be investigated. These factors are highly dependent on the quality of construction work, and have been shown to have a large influence on the covercrete permeability, and hence durability.

Figure 3.1 shows an overview the experimental programme adopted in this study.



EXPERIMENTAL AIMS

Investigate the sensitivity of OPI test and Torrent method to various intrinsic and extrinsic concrete properties; develop a correlation between the two gas-permeability based methods; propose improvement of the DI approach by incorporating the Torrent method.

EXPERIMENTAL PROGRAMME

Experimental variables and constants

- Constants: Aggregate type and content
- Variables: Cement type, w/c ratio (cement content), compaction, environmental exposure, testing age

Experimental details

- Cement type: 100 % PC, 50/50% PC/GGBS (using CEM I 52.5N)
- w/c ratio: 0.50, 0.65, 0.80
- Aggregate type : (1) Coarse – 19mm Greywacke
  (2) Fine – Klipheuwel sand
- Sample size: (1) 150 x 150 x 150 mm (two per test condition)
  (2) 100 x 100 x 100 mm (three per test condition)

TESTING PROCEDURE

TEST PARAMETER	TEST METHOD	UNITS
(1) Gas-permeability	Oxygen permeability index	m/s
(2) Gas-permeability	Torrent method	m^2
(3) Electrical resistivity	Four-point (Wenner) probe method	kΩ.cm
(4) Electrical impedance	Mass moisture	% moisture
(5) Relative humidity, temperature	Hygrometer	% moisture, °C
(6) Compressive strength	Cube crushing	MPa

EXPECTED OUTCOMES

Greater insight into the effects of intrinsic and extrinsic test variables on gas-permeability measurements; development of a correlation between OPI and Torrent methods; an empirical basis for improvement to the DI approach by incorporation of the Torrent method.

Figure 3.1: Overview of experimental programme

3.2 Sample preparation and preconditioning

Photographs from testing performed at the University of Cape Town may be found in Appendix C (Section 10.1).

3.2.1 Concrete mix design

The concrete mix design was developed with the key guidelines (discussed in Section 3.1) in mind. A short description of each of test variables (and their influence) is provided.

(i) Cement type

Two common concrete cement types (for durability critical structures) were used, namely (Addis, 1998; Mackechnie, 2001; Grieve, 2009):

- 100 % Plain Portland cement (PC) CEM I 52.5N
- 50/50 % Portland cement (PC) CEM I 52.5N / Ground granulated blastfurnace slag (GGBS)

PC was selected due to its extensive usage in the past, and serves as a reference concrete. GGBS is commonly used for mass concrete structures, and for structures where durability is deemed critical (e.g. marine structures) (Mackechnie, 2001). CEM I 52.5 N Portland cement was obtained from the Riebeeck Pretoria Portland Cement Co Ltd. (PPC) factory in Cape Town, South Africa. The chemical composition for this cement is shown in Table 3.1 (further details in Appendix B (Section 9.1)). Terminology and abbreviations are described in Section 2.4.1.

Table 3.1: PPC CEM I 52.5 N chemical composition (Data courtesy of S. Crosswell at PPC (2012))

Oxide		% Composition
Silica	SiO_2	21.10
Alumina	Al_2O_3	4.00
Iron Oxide	Fe_2O_3	3.35
Lime	CaO	65.80
Magnesia	MgO	0.87
Sulphate content	SO_3	2.30
Chloride content	Cl^-	0.01
Potassium	K_2O	0.70
Sodium	Na_2O	0.10

GGBS (a by-product of the blastfurnace process) is a latent hydraulic binder, of similar particle size to that of PC (Neville, 1981). It has been found highly effective for construction of mass concrete structures (e.g. dam construction), in particular, where a reduction in the heat of hydration is desirable (Mackechnie, 2001; Grieve, 2009). A 50/50 % PC/GGBS blend is commonly used in South Africa (Mackechnie, 2001). The GGBS was obtained from AfriSam in Roodepoort, Johannesburg, South Africa. The chemical composition for this cement is shown in Table 3.2 (further details in Appendix B (Section 9.2)). Terminology and abbreviations are described in Section 2.4.1.

Table 3.2: AfriSam Slagment (GGBS) chemical composition (Data courtesy of J. Ungerer (2012))

Oxide		**% Composition**
Silica	SiO_2	39.45
Alumina	Al_2O_3	12.84
Iron Oxide	Fe_2O_3	0.36
Lime	CaO	38.89
Magnesia	MgO	7.84
Sulphate content	SO_3	0.18
Chloride content	Cl	-
Potassium	K_2O	0.92
Sodium	Na_2O	-

In previous studies, cement type has been varied in order to investigate the sensitivity of electrical resistivity to binder type (Denarie et al., 2011). Resistivity has been used to ensure that the concrete is 'sufficiently' dry (in accordance with the Swiss approach), for testing with the Torrent method. The use of a GGBS cement should therefore provide further insight into the relationship between cement extender, moisture content and electrical resistivity (Section 2.6.5). GGBS has also been found highly sensitive to curing efficiency, and hence an important property for ensuring covercrete impermeability (Grieve, 2009; Kellerman, 2009).

(ii) Water/cement ratio

The water/cement (w/c) ratio has an influence on strength development, and the impermeability of concrete (Richardson, 2002; Grieve, 2009; Neville et al., 2010). According to SANS 10100-2 (1992) for 100% PC and 50/50% PC/GGBS, the recommended limiting w/c ratio for heavily polluted air (e.g. areas around coal-burning power stations) is 0.56. This may be considered a worst case exposure for structures susceptible to carbonation induced corrosion. The generally accepted range for w/c ratio, where durability requirements are to be considered, may be taken as 0.40 to 0.60 (Addis 1998; Romer 2005).

Three w/c ratios were selected, specifically: 0.50, 0.65 and 0.80. These are higher than may be expected for structures exposed to harsh environmental exposure conditions, however, previous studies (Section 2.9) suggest that a lower w/c may provide only a small range of permeability data (well below the recommended limiting values by DI approach and Swiss approach). In addition, it was expected that concrete gas-permeability may be quite sensitive to w/c ratio, based on results by previous studies (Romer, 2005; Beushausen et al., 2008).

(iii) Coarse aggregate

The effect of coarse aggregate content on permeability is not well understood (Section 2.5.4). It was for this reason that coarse aggregate content was kept constant. The aggregate content was selected in accordance with the Cement and Concrete Institute (C&CI) Method for mix design (Addis et al., 2009).

19mm Greywacke aggregate (commonly known as Malmesbury Shale) was supplied by AfriSam, from the Peninsula quarry in Cape Town. It is a fine-grained, glassy rock, which crushes to form thin elongated aggregate particles (Grieve, 2009). The aggregate complies with SANS 1083 (1994) for coarse aggregate grading. This is shown in Figure 3.2, by means of a typical 19mm Greywacke aggregate grading curve. Details from the sieving analysis can be found in Appendix B (Section 9.3).

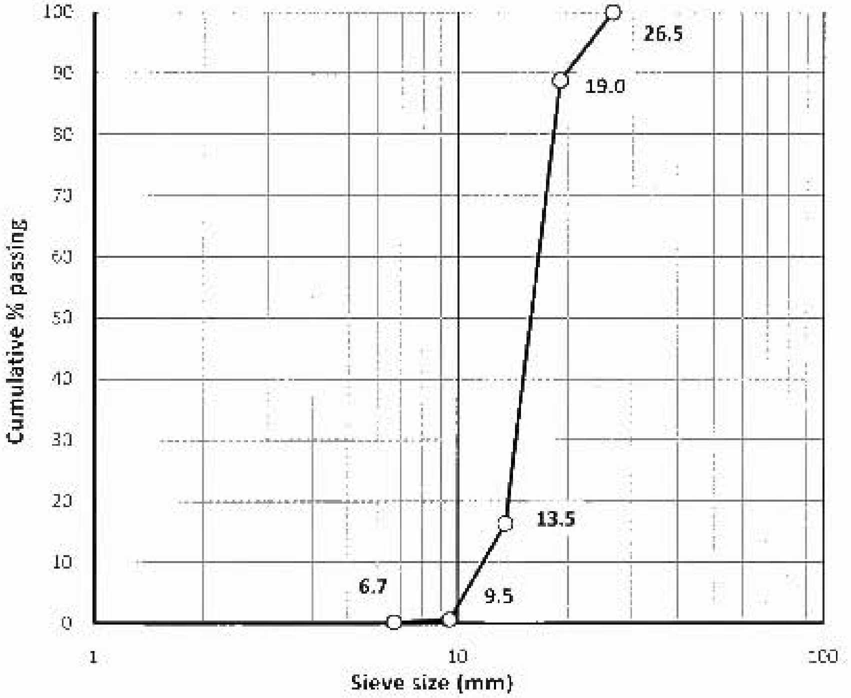


Figure 3.2: 19mm Greywacke grading curve (data courtesy of UCT concrete laboratories (2010))

(iv) Fine aggregate

Fine aggregates are known to have a significant effect on fresh concrete moisture absorption, as well as moisture related deterioration mechanisms (Grieve, 2009). Fine aggregates, in accordance with SANS 1083:2006, should meet specific requirements for grading, dust content, methyl blue absorption, clay content, chloride content and organic impurities.

Klipheuwel sand was used in this study, as it is one of the most common sands used in the Cape Peninsula. The source of this aggregate is in Durbanville, South Africa. These sands have good particle shape and continuous grading, however, they are known to have a high fines content. Figure 3.3 shows a typical Klipheuwel sand grading curve. Details from the sieving analysis can be found in Appendix B (Section 9.4).

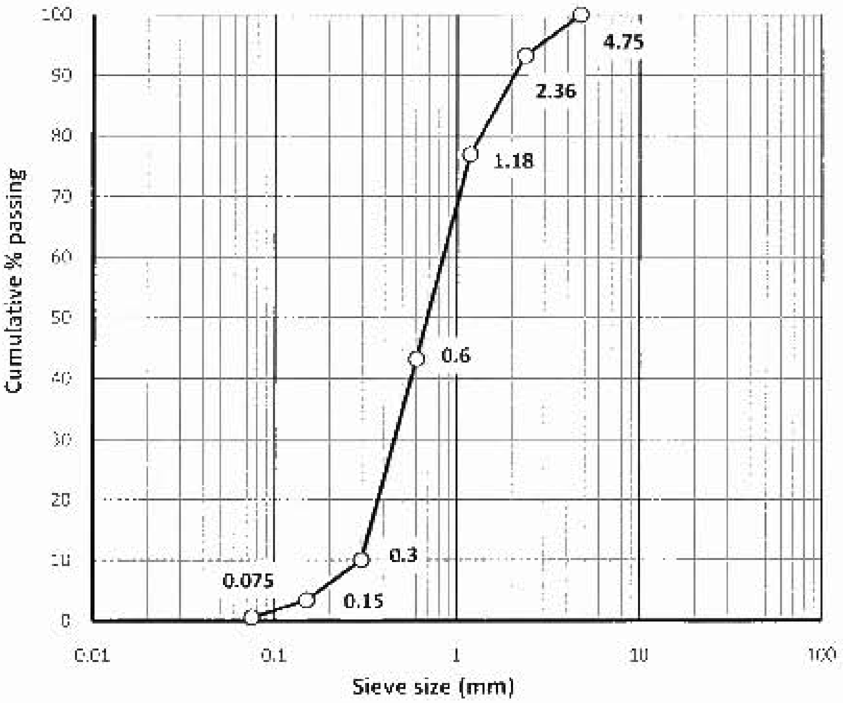


Figure 3.3: Klipheuwel sand grading curve
(data courtesy of UCT concrete laboratories (2010))

(v) Concrete mix proportions

The Cement and Concrete Institute (C&CI) Method (Addis et al., 2009) is commonly used for mix design in South Africa, and hence was used in this study. In this method, guidelines are presented to aid material selection and specification, after which a volumetric proportioning of aggregates, water demand, w/c ratio, cement type and content, and sand content is performed.

Of particular importance for this study was maintaining a slump of 80 ± 20mm, as commonly specified by the concrete industry. The slump test procedure is given in SANS 5862-1:2006. Specifying a slump of 80 ± 20mm ensures the mix has good consistency, and that the mix is not too dry (or stiff) such that honeycombing may occur. In the case of a high slump, sand was added incrementally until the minimum slump requirements were met. This was necessary for the higher w/c ratio mixes (viz. 0.60 and 0.80). The final design mixes were adjusted accordingly.

The mix specification used has been provided in Table 3.3. For mixes 4 to 6 additional sand was added to reduce the slump measurement to within 80 ± 20mm, as shown.

Table 3.3: Generalised mix specification

	PC	GGBS	Total Cement	Water	w/c ratio	Course agg.	Fine agg.	Slump achieved	Mix volume
Relative densities	*3.14*	*2.9*				*2.71*	*2.65*		
Mix No.	kg	kg	kg	kg	-	kg	kg	mm	L
1	17.0		17.0	8.5	0.50	52.5	43.3	83	49.6
2	8.5	8.5	17.0	8.5	0.50	52.5	42.7	64	49.6
3	13.1		13.1	8.5	0.65	52.5	45.6	60	49.3
4	6.5	6.5	13.1	8.5	0.65	52.5	47.1	100	50.0
5	10.6		10.6	8.5	0.80	52.5	52.5	80	51.1
6	5.3	5.3	10.6	8.5	0.80	52.5	52.2	81	51.1

The total mix volume for the simulated summer and winter mixes were approximately 50 and 30ℓ respectively.

3.2.2 Batching, mixing and casting

Both coarse and fine aggregates were dried for a minimum of 24 hours in an oven (at 100°C). Concrete production was performed in accordance with SANS 10100-2:1992, and SANS 5862:2006 (parts 1-3).

Batched materials were placed inside a 50ℓ pan mixer, and mixed well to ensure good consistency and an acceptable slump value (80 ± 20mm). It has been recognised that compaction on site is often inadequate to remove the entrapped air voids which result in high covercrete permeability. As mentioned in Sections 2.2.1 and 2.5.5, entrapped air voids act as a 'bridge' between otherwise disconnected pore segments and hence increased permeability. Since the objective of this study is the practical implementation of an integrated approach, it was considered critical to investigate concretes which closely resemble those expected in situ. In this study, two compaction methods were considered.

'Good' compaction was performed using a table vibrator, which is expected to remove most of the entrapped air (more than that expected in regular construction). 'Poor' compaction was performed as follows (this will be referred to as the 'drop' test):

1. Concrete was carefully placed the cube moulds, and pressed in lightly to ensure no large voids were present, particularly in the lower corners of the mould.
2. Each cube was dropped five times from approximately 100mm.
3. The concrete cast surface was then levelled using a trowel.

Figure 3.4 shows two identical concrete cubes, with the only variable being compaction method. The presence of entrapped air voids on the surface of the poorly compacted cube (right) provides support for the unconventional compaction method developed. As far as possible, it was ensured that both compaction methods were performed consistently across all mixes, such that the concrete samples are comparable. Subsequently, it was found that the compaction methods did not perform as expected in this study, and hence, will be referred to as compaction methods 1 and 2 from this point onwards. More details can be found in Appendix D (Section 11.3).

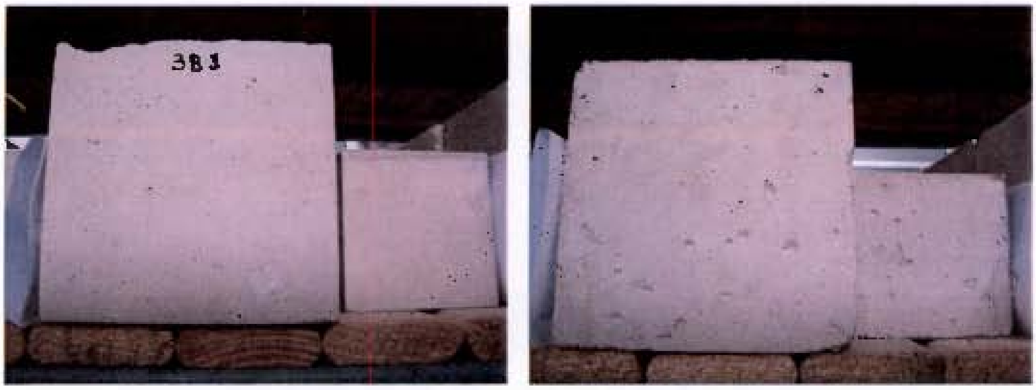


Figure 3.4: Photograph showing good (left) and poor (right) compaction

For each test condition, two 150mm (for durability tests) and three 100mm (for compressive strength) cubes were cast. It was important to consider the effect of sample size on the durability test methods selected. In particular, the test method which governed sample size was found to be the Torrent method. This is due to 100mm diameter outer seal on the vacuum head. In consultation with Dr. Torrent (Torrent, 2012), 150mm cubes were deemed suitable for testing using the PermeaTORR instrument, and no sealing of cube edges was necessary. The sample size chosen (150mm cube) had the following benefits:

1. The PermeaTORR was sufficiently far from the edges to avoid interference by airflow from adjacent sides.
2. Each sample allowed two OPI test cores to be extracted, and hence four OPI test specimens (the minimum required by the DI approach).
3. The four-point (Wenner) probe method (using the commercially available Proceq Resipod) was possible if measured diagonally across the cube surface. The spacing from outer probes is approximately 150mm. See Appendix C (Section 10.2) for further details

Testing 150 mm cubes was performed in order to simulate a concrete wall (or beam) member. This is illustrated in Figure 3.5. It should be noted that for this study, the cast face itself (as shown) was not tested.

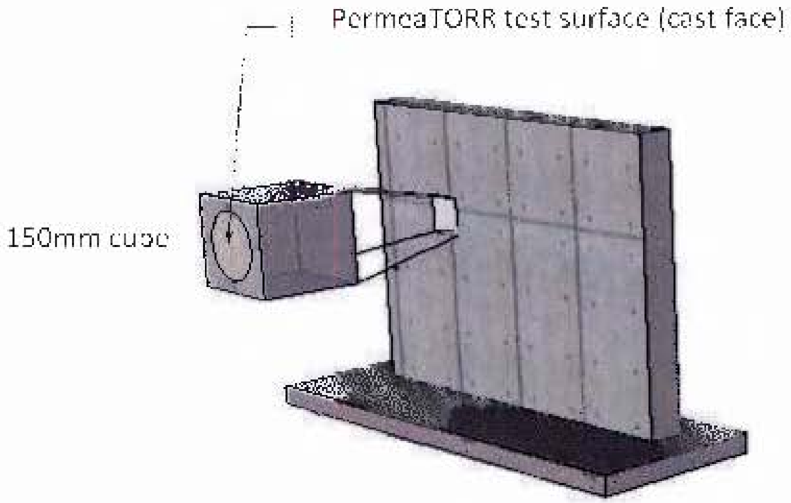


Figure 3.5: Simulation of a wall section using 150 mm laboratory cubes

All concrete cube samples were allowed to cure for approximately 24 hours before removing from the moulds. In particular, the 0.80 w/c ratio mixes presented problems with demoulding after 24 hours due to the slow rate of hydration. These were allowed an additional 24 hours to hydrate before demoulding.

3.2.3 Curing and simulated environmental exposure

Two environmental exposure conditions were simulated, in order to investigate (1) the effect of curing regime, and (2) the effect of concrete moisture content at testing. Of particular importance was the effect of concrete moisture content on the Torrent method. Moisture has a pore 'blocking' effect on gas-permeation in concrete, and has presented a degree of uncertainty with regards to interpretation of permeability results (Section 2.5.7). This test variable may therefore provide insight into the sensitivity of the integrated approach to variation in environmental exposure conditions.

Two typical environments were simulated, those being 'summer' and 'winter' conditions in Cape Town, South Africa. Since no formal curing was performed, the degree on hydration would be largely dependent on the moisture available from the exposure environment. For a structure where no formal curing is performed, these exposure conditions may be considered representative of 'best' and 'worst' case natural curing expected on-site.

Summer samples were tested at 35 and 90 days, while winter samples tested at 40 days. As recommended by Alexander et al. (2008), testing as-built structures should be carried out between 28 and 35 days. Testing on summer samples was again repeated at 90 days to investigate the effect of ageing on gas-permeability. Winter testing was initiated at 35 days, however, since 5 days were required for samples to meet Swiss approach specifications, testing only began at 40 days (See Appendix D (Section 11.4)).

(i) Summer simulated environmental exposure

The aim of the 'summer' environment was to simulate worst case natural curing on-site, and observe the sensitivity of selected test methods. Concrete samples were cast during the summer months (December to February) in Cape Town, South Africa. After 24 hours concrete samples were demoulded, and placed directly into a controlled environment (53 ± 2 % RH, 20 ± 2 °C). Figure 3.6 shows samples placed in the controlled environment. These samples were tested at both 35 and 90 days age, to investigate the sensitivity of the selected test methods to concrete age.

Figure 3.6: Simulated summer environment (53 ± 2% RH, 20 ± 2 °C)

(ii) Winter environment

The aim of the 'winter' environment was to simulate best case natural curing practice and observe the sensitivity of the selected test methods. Samples were cast during the winter months (June to August) in Cape Town, South Africa. After 24 hours the samples were demoulded, and placed unprotected in the natural environment. The mean low and high temperatures, during this period, were 8 and 18°C respectively (WeatherSpark, 2013). Samples were sprayed with water each day, until no visible absorption took place on the surface of the sample. On days where natural rainfall occurred, no additional wetting was performed. Wetting was performed to ensure each cube remained moist until testing, and thereby simulate expected seasonal weather conditions in Cape Town. Figure 3.7 shows the concrete samples placed in the simulated winter environment.

Figure 3.7: Simulated winter environment

After 35 days in the simulated winter environment, cubes were measured using surface moisture instruments (in accordance with Swiss Standard SIA 262/1) and found too moist for testing using the Torrent method (Section 2.6.5). Samples were then placed inside the controlled environment (53 ± 2 % RH, 20 ± 2 °C), and moisture measurements taken daily. After 5 days the samples were deemed 'sufficiently' dry to perform testing. See Appendix D (Section 11.4) for further details.

3.3 Testing and data collection

3.3.1 Oxygen permeability index test

A detailed discussion of the OPI test has been provided in Section 2.6.4. The test procedure is described in the 'Durability Index testing manual (Version 2.0)' by Alexander et al. (2010). Limiting values and acceptance criteria were based on those prepared for the 'South African National Roads Agency Limited performanced-based durability specifications' (SANRAL, 2010). These specifications (although project specific) provide a good indication of the generally accepted values for the DI approach as implemented in South Africa. For extracts from the SANRAL specifications see Appendix A (Section 8).

A brief summary of the testing procedure is provided:

1. Torrent gas-permeability; electrical resistivity; and electrical impedance were measured on each 150 mm cube. Cube crushing was performed on corresponding 100 mm cubes. Two cores were taken from each cube sample. The cores were not extracted through the cast surface, to eliminate the high variability between cast surface and bottom surface (due to the effects of settlement and bleeding). The core extraction on 150 mm cubes is shown in Figure 3.8.

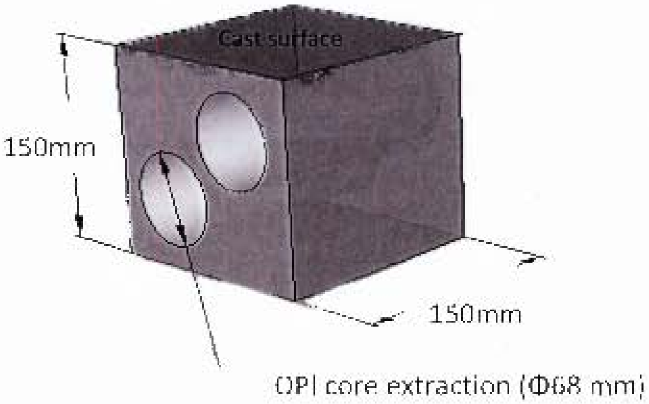


Figure 3.8: Oxygen permeability index coring from 150 mm cube

2. From each core, the outer 5mm edge was removed (in accordance with the specifications for DI specimen preparation). A slice (30 ± 2mm) was then cut from each of the edges. This allowed preparation of four OPI test specimens from each 150 mm cube. It was observed that both core extraction and test specimen preparation performed on high w/c mixes, may result in 'chipping' of the test specimen edge. Figure 3.9 shows a correctly prepared OPI test specimen.

Figure 3.9: Correctly prepared oxygen permeability index test specimen

3. OPI test specimen preparation, preconditioning and the oxygen permeability test method are described in Section 2.6.4. Photographs from testing performed at the University of Cape Town can be found in Appendix C (Section 10.1).

3.3.2 Torrent method testing

A detailed discussion of the Torrent method has been provided in Section 2.6.5. The operation of the PermeaTORR instrument is outlined in 'Measures the air-permeability of the cover concrete and other porous materials: Swiss Standard method SIA 262/1-E: User manual v3.0' by M.A.S (2010). The test procedure (with regards to conformity rules, moisture condition, and limiting criteria) are outlined in

'Specification and site control of the permeability of the cover concrete: The Swiss approach' by Torrent et al. (2012).

A brief summary of the testing procedure is provided:

1. After 35 and 90 days (in the 'summer' simulation) and 40 days (in the 'winter' simulation), the 150mm concrete cubes were tested using selected non-destructive test methods. These are shown in Table 3.4.

Table 3.4: Non-destructive test methods for study

Parameter	*Test method*	*Test instrument*
(1) Gas-permeability	Torrent method	PermeaTORR (M.A.S)
(2) Electrical resistivity	Four-point (Wenner) probe method	Resipod (Proceq)
(3) Electrical impedance	Mass moisture	Elcometer CME4 (Tramex)

2. A single PermeaTORR measurement was taken on three of the adjacent cube faces (excluding the cast face and bottom surface). Each of these test faces were also tested using each of the methods presented in Table 3.4. A brief description of the non destructive test methods (used for moisture measurement) is provided in Appendix C (Section 10.2). Figure 3.10 shows selection the test faces, and preferable positioning of the PermeaTORR vacuum head.

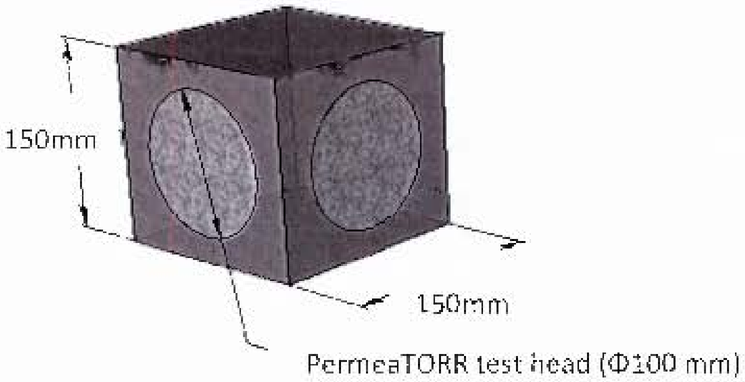


Figure 3.10: PermeaTORR selection of test surfaces

3. The PermeaTORR vacuum head requires a relatively smooth surface in order for the outer chamber to achieve an airtight seal. In the case of the poorly compacted concrete cubes, surface voids may require repositioning of the vacuum head in order to achieve an adequate seal. This is likely to be less of a concern for 'real' in-situ testing as larger test areas are available. Figure 3.11 shows the vacuum head after repositioning on the test surface due to surface voids.

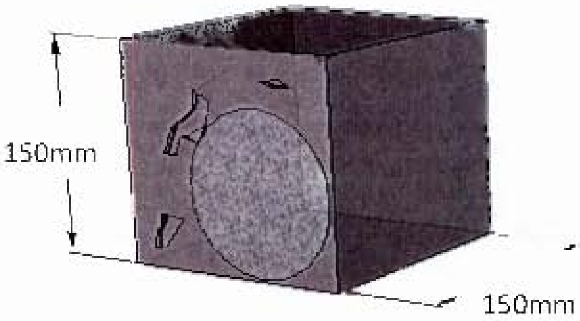


Figure 3.11: PermeaTORR repositioning of vacuum head due to surface voids

4. Details for moisture measurement and the Torrent method are described in Section 2.7. Photographs from testing performed at the University of Cape Town can be found in Appendix C (Section 10.1)

3.4 Summary of experimental programme

The experimental programme presented aims to investigate the sensitivity of OPI test and Torrent method to various intrinsic and extrinsic concrete factors; allow development of a correlation between the two gas-permeability based methods; and provide an empirical basis for improvement of the DI approach.

Appendices B and C provide more information regarding the cement and aggregate properties and testing methods.

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter provides a detailed overview of the results achieved using the experimental programme described in Chapter 3. Results from the OPI test, Torrent method, as well test methods used to account for moisture are presented. These results are presented as a basis for the integrated approach which follows.

4.2 Analysis of OPI test data according to Durability Index approach

This section outlines the effect of intrinsic factors (w/c ratio, cement type) and extrinsic factors (curing, compaction) on the oxygen permeability index test. A brief description of the method for outlier detection may be found in Appendix D (Section 11.1).

4.2.1 Overview of OPI test results

In accordance with the current project specifications for SANRAL (Appendix A, Table 2.6), the minimum OPI requirements for structures designed to resist carbonation-induced corrosion may be generalised as follows:

- OPI_{min} = 9.0 (k_{OPI} = 10.0 x 10^{-10} m/s); recommended minimum cover depth = 40mm; for exposure conditions XC1-XC3.
- OPI_{min} = 9.2 (k_{OPI} = 6.3 x 10^{-10} m/s); recommended minimum cover depth = 45mm; for exposure condition XC4.

Figure 4.1 shows that based on the minimum requirements (for the XC4 exposure class), most of the summer environment 50/50% PC/GGBS concretes would be deemed unacceptable. In addition, the summer 100% PC 0.80 w/c ratio concretes are relatively close to the limiting value for exposure class XC4. It is interesting to note that in this case (for the summer 100% PC 0.80 w/c ratio concretes), the effect of ageing resulted in a large enough reduction of gas-permeability to pass the concrete at 90 days. This highlights the importance of specifying testing age, to ensure gas-permeability results are not evaluated erroneously. The DI approach allows for an age-adjustment in the service life prediction model.

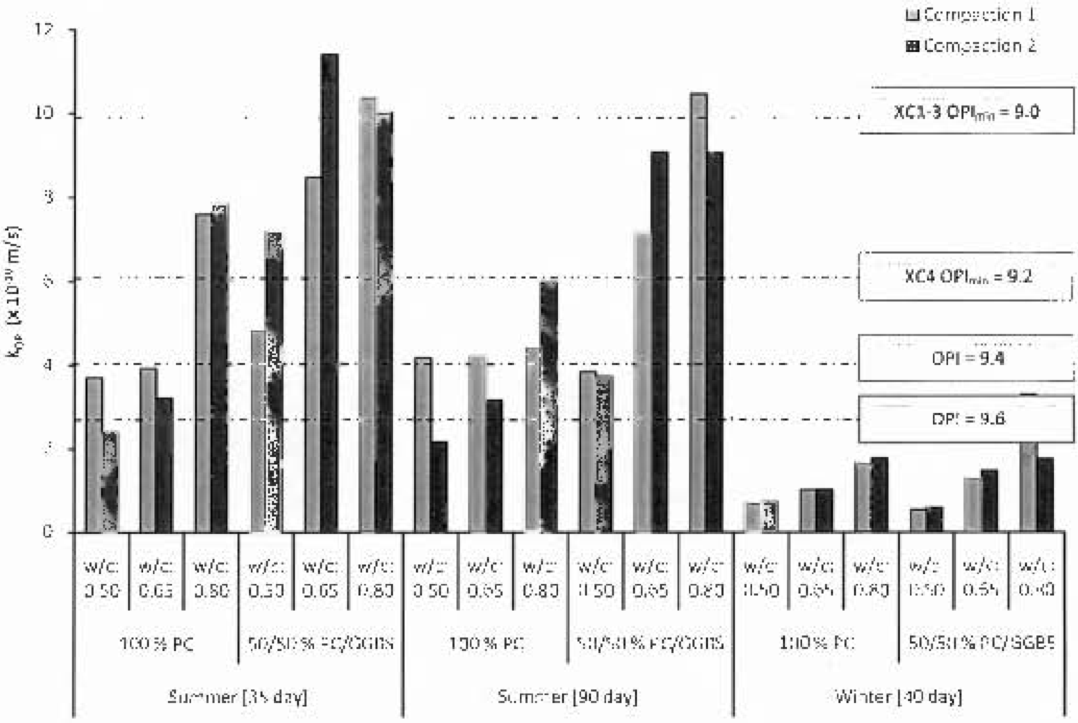


Figure 4.1: Overview of k_{OPI} experimental results

As mentioned previously, it was found that the experimental method used to obtain various degrees of compaction (Section 3.2.2) did not provide the expected results (viz. lower gas-permeability for concretes of a higher degree of compaction). Figure 4.1 shows the varied effect of compaction on OPI measurement. In the sections which follow, compaction methods are addressed as only compaction methods 1 and 2. This will be discussed further in the sections to follow.

4.2.2 Sensitivity of OPI test to experimental variables

(i) Cement type

Figure 4.1 reveals clear distinction between gas-permeability (k_{OPI}-value) for concretes made with 100% PC and 50/50% PC/GGBS cement types. For the summer environmental exposure conditions, the results show a lower k_{OPI}-value for the 100% PC concrete in comparison with 50/50% PC/GGBS. In the winter condition, the 100% PC and 50/50% PC/GGBS permeability values were quite similar.

The addition of GGBS is known to reduce the rate of hydration (GGBS being a latent hydraulic binder). Figure 4.1 shows a greater reduction in gas-permeability from 35 to 90 day summer 50/50% PC/GGBS concretes, in comparison with the 100% PC concretes.

Further, GGBS concretes are known to be highly sensitive to curing efficiency. The importance of good quality curing is evident by the large discrepancy between summer 100% PC and 50/50% PC/GGBS concrete k_{OPI}-values. A markedly lower discrepancy for the better cured winter environmental condition exists.

(ii) w/c ratio

The OPI test reveals clear distinction between k_{OPI}-values for w/c ratios 0.50, 0.65 and 0.80. It is expected that a lower w/c ratio will result in a reduction in concrete gas-permeability, which is clearly illustrated in Figure 4.1.

(iii) Compaction

It is expected a higher degree of compaction will result in a denser hardened concrete, and hence a lower k_{OPI}-value. Figure 4.1 shows the relationship between gas-permeability and compaction efficiency for each environmental exposure condition. As mentioned, the method used to obtain various degrees of compactions appears unsuccessful, and hence will be referred to as compaction methods 1 and 2. More information is available in Appendix D (Section 11.3).

(iv) Environmental exposure

The 35 day summer and 40 day winter results are compared to illustrate the effect of natural curing on each of the concretes. For the summer environment, samples were placed in a controlled environment (53 ± 2 % RH, 20 ± 2 °C) for 35 days, at which point the concrete is expected to contain very little moisture. Due to the age of the concrete and its relatively dry state, it expected that little hydration would take place between 35 and 40 days. This assumption may be justified by the small reduction of permeability between summer 35 day and summer 90 day samples, as shown in Figure 4.1.

Figure 4.1 does, however, show a clear reduction of gas-permeability by improved 'curing'. As expected, the 50/50% PC/GGBS concrete is strongly affected by lack of curing. It also appears that the detrimental effect of poor curing becomes greater with increasing w/c ratio. The effect of moisture at the time of testing is not considered, due to the preconditioning required by the DI approach specifications (Chapter 3).

(v) Testing age

It is well understood that as concrete ages, so the hydration process should result in reduced concrete permeability. The rate of hydration decreases exponentially with increasing age, which suggests that at some point the effect of ageing becomes negligible. After 35 days, the 100% PC concretes would have reached a higher degree of hydration than for the 50/50% PC/GGBS cement, due to the effect of GGBS on the slowed rate of hydration. Figure 4.1 shows that ageing had an appreciable effect on 50/50% PC/GGBS concretes, resulting in reduction of gas-permeability, especially at lower w/c ratios. This was less the case for 100% PC concretes.

4.3 Analysis of Torrent method test data according to Swiss approach

This section outlines the effect of intrinsic factors (w/c ratio, cement type) and extrinsic factors (curing, compaction) on the Torrent method. A brief description of the method for outlier detection may be found in Appendix D (Section 11.1).

4.3.1 Overview of Torrent method results

In accordance with the Swiss approach recommendations for structures designed to resist carbonation-induced corrosion may be summarised as follows:

- $k_{TI,\,min} = 2.00 \times 10^{-16}\ m^2$ for exposure conditions XC4. Exposure conditions XC1-XC3 require only a specified minimum cover depth (no limiting gas-permeability value).

Figure 4.2 shows that based on these minimum requirements, the complete set of 35 day and 90 day summer concretes would be deemed unacceptable (with the exception of the 100% PC 0.50 w/c ratio concretes). The current Swiss approach recommendations for structures designed to resist carbonation-induced corrosion appear markedly more conservative than those according to the Durability Index approach (Section 4.2.2.). This disparity will be addressed in detail in Section 4.5. Figure 4.3 shows the sensitivity of the Torrent method to lower permeability winter concrete samples only.

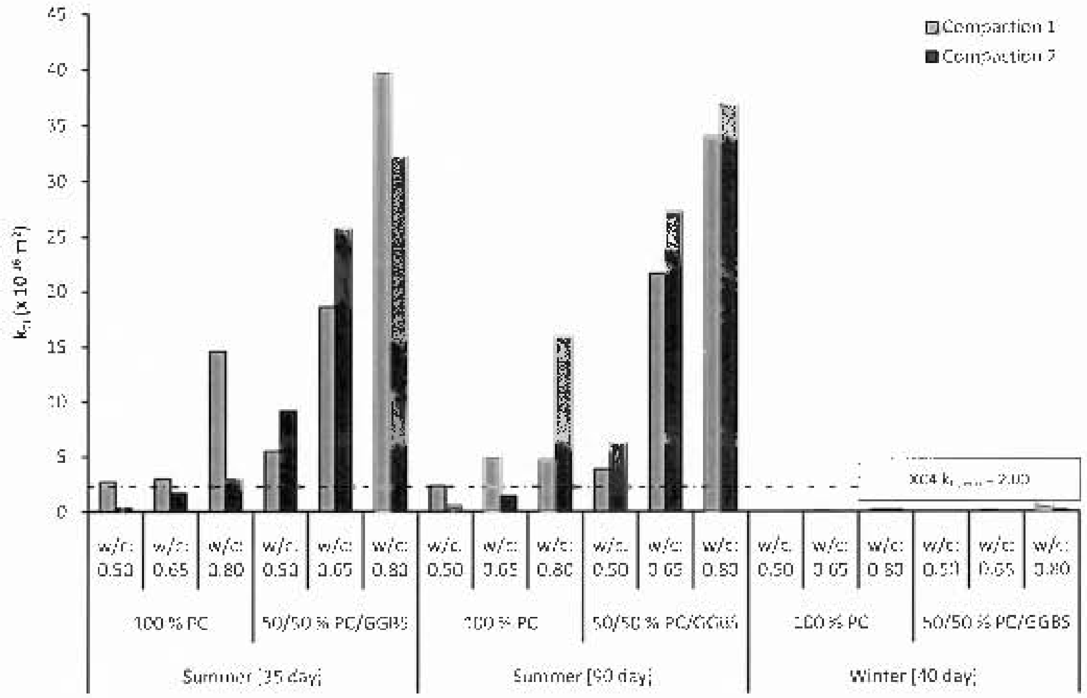


Figure 4.2: Overview of k_{TI} experimental results

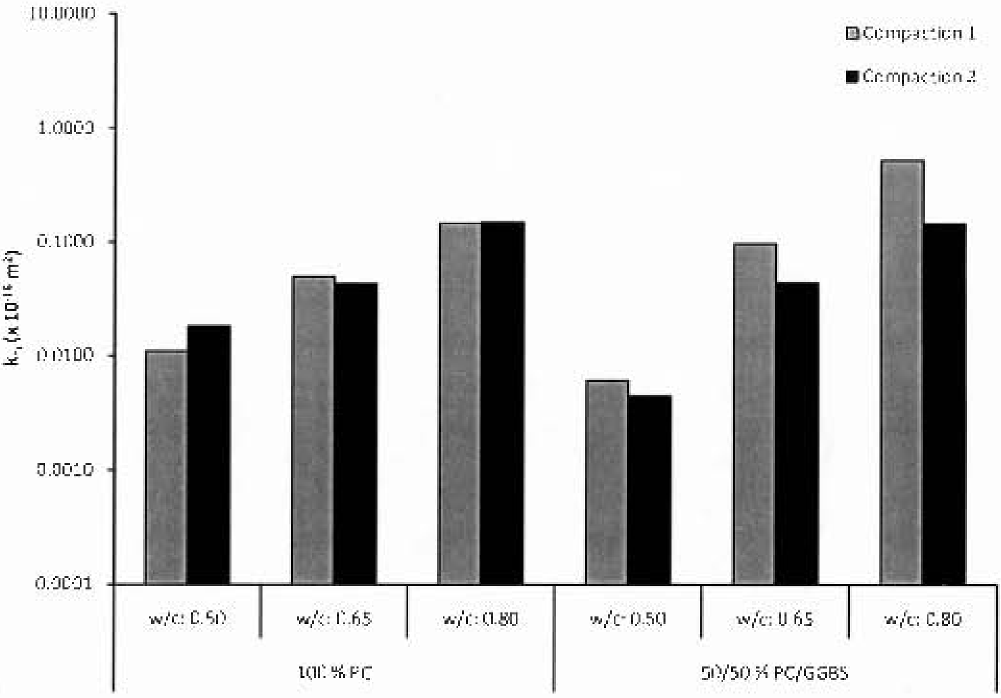


Figure 4.3: Overview of k_{Ti} winter exposure condition experimental results

Careful attention should be paid to the winter (40 day) k_{Ti} measurements. Based on Figure 4.2, it could be concluded that the permeability classification is in fact the same for all winter concretes. However, as shown in Table 2.7, the k_{Ti} permeability classes are separated by one order of magnitude. The winter measurements generally range between 0.01 (for very low permeability) and 1.0 (for high permeability), extending across four permeability classes. This is shown in Figure 4.3. For this reason, careful attention should be paid to all discussions regarding low Torrent permeability values, to ensure that these are not analysed erroneously.

It should also be noted that all moisture requirements as specified by the Swiss approach (Torrent et al., 2012) were met. These may be summarised as follows:

1. Using electrical impedance with an instrument such as the concrete encounter instrument (e.g. Tramex CME4 Elcometer), the moisture content (by % mass) should not exceed 5.5%.
2. Using electrical resistivity with a Wenner probe instrument (e.g. Proceq Resipod), the lower limit electrical resistivity values of 10 and 20 kΩ.cm apply to CEM I (viz. PC without reactive mineral additions) and blended cements (e.g. PC with cement extender FA) respectively. If the temperature is not between 15°C and 25°C, an appropriate conversion of electrical resistivity is described.

4.3.2 Sensitivity of Torrent method to experimental variables

(i) Cement type

The Torrent method reveals clear distinction between gas-permeability (k_{Ti}-value) for concretes made with 100% PC and 50/50% PC/GGBS cement types for the summer environmental exposure. For all three environmental exposure conditions, Figure 4.2 shows a lower k_{Ti}-value for the 100% PC concrete. However, as it will be shown in Section 4.4, it appears that the type of cement may influence the concretes ability to hold water, and hence the effect of cement type cannot be isolated. This moisture influence may in fact skew the effect of cement type on k_{Ti} permeability.

As discussed in Section 4.2.2 (i), the addition of GGBS is also known to reduce the rate of hydration (GGBS being a latent hydraulic binder). Figure 4.2 shows a greater reduction in gas-permeability for 35 day and 90 day summer 50/50% PC/GGBS concretes, in comparison with the 100% PC concretes. In fact, for the 100% PC concretes the data suggests almost a negligible reduction in permeability after 35 days in the summer environment.

Further, GGBS concretes are known to be highly sensitive to curing efficiency. The importance of good quality curing is again evident by the large discrepancy between summer 100% PC and 50/50% PC/GGBS concrete k_{Ti}-values, while a markedly lower discrepancy for the better cured winter environmental condition. It should be noted, however, that these results are also affected by the moisture content of the concrete at the time of testing. This will be discussed further in Section 4.4.

(ii) w/c ratio

The Torrent method reveals clear distinction between k_{Ti}-values for w/c ratios 0.50, 0.65 and 0.80. It is expected that a lower w/c ratio will result in a reduction in concrete gas-permeability, which is illustrated in Figure 4.2 and 4.3. As mentioned above, the effect of moisture (albeit minor), cannot be ignored in order to isolate the effect of w/c ratio on k_{Ti} permeability alone.

(iii) Compaction

It is expected that a higher degree of compaction will result in a denser hardened concrete, and hence a lower k_{Ti}-value. The method used to obtain various degrees of compaction appears unsuccessful (as was the case for the OPI test) and hence will be referred to as compaction method 1 and 2 in the sections to follow. This is shown in Figure 4.2. More information is available in Appendix D (Section 11.3).

(iv) Environmental exposure

The 35 day summer and 40 day winter results are compared to illustrate the effect of curing on each of the concretes. Justification for comparing different age concretes is provided in Section 4.2.2 (iv). In this comparison of environmental exposure there are two contributing factors:

1. The moisture available during hydration. The winter condition provided moisture which increases the degree of hydration, and hence reduces the concrete permeability.
2. The moisture content of the concrete at testing, where an increased moisture content results in pore 'blocking' of the capillary voids, and hence a lower gas-permeability.

The combined effect is a significantly lower k_{TI}-value for the winter environment. In addition, the k_{OPI} -value appears less sensitive to environmental exposure, which may be attributed to the removal of moisture influence by preconditioning of the OPI test specimens (the second factor mentioned above). Again, the effect of magnitude could be very misleading in a comparison of k_T values (see Table 2.7).

(v) Testing age

It is understood that as concrete ages, so the hydration process should result in reduced concrete permeability. However, in the investigation of testing age on Torrent method there are two contributing factors:

1. As the concrete ages, so it is expected that the concrete continues to hydrate (even if at a very reduced rate to that experienced at early ages). This results in reduced concrete permeability.
2. The moisture content of the concrete at testing, where an increased moisture content results in pore 'blocking' of the capillary voids, and hence a lower gas-permeability.

In consideration of the results presented in Section 4.2.2 (v), it would appear that between 35 days and 90 days the increase in gas-permeability due to evaporation of pore water has a greater effect on the k_{TI}-value than the reduction of gas-permeability due to improved pore structure. This is shown in Figure 4.2.

4.4 Moisture content assessment in accordance with the Swiss approach

The effect of concrete moisture content on the Torrent method has been extensively researched in the past. The results presented in Section 4.3 suggest that moisture may still have an influence on gas-permeability even within the recommended criteria presented in the Swiss approach. This does not apply to the OPI test, due to the requirements preconditioning of test specimens.

4.4.1 Electrical resistivity

The Four point (Wenner) probe method was used to measure the surface electrical resistivity (kΩ.cm). The instrument selected was the Resipod by Proceq.

(i) Overview of electrical resistivity results

Based on the Swiss recommendations for limiting moisture content (Section 2.7.1), all moisture requirements were met. For the summer environmental exposure this was expected, as the concrete would have not been exposed to moisture since being cast. This would allow sufficient time for moisture to be used in the hydration process, as well as for evaporation of the capillary water after hardening.

In the winter environmental exposure, the samples required 5 days inside a controlled environment (with no exposure to moisture) in order to achieve the minimum moisture content. It is recommended that clear distinction be made between the mean and minimum electrical resistivity values when used for moisture assessment. Mean resistivity may be taken as an average over a given test area, while the minimum be taken as the lowest of the measurements recorded from within a given test area. At 35 days, electrical resistivity measurements were taken on all winter samples. The mean resistivity (grouped according to cement type, viz. 50/50% PC/GGBS or 100% PC), was found to meet the Swiss approach recommendations at 35 days. However, it was considered more important to evaluate acceptance on the minimum electrical resistivity value (since drying increases resistivity).

An overview of the electrical resistivity measurements at the age of testing is shown in Figure 4.4.

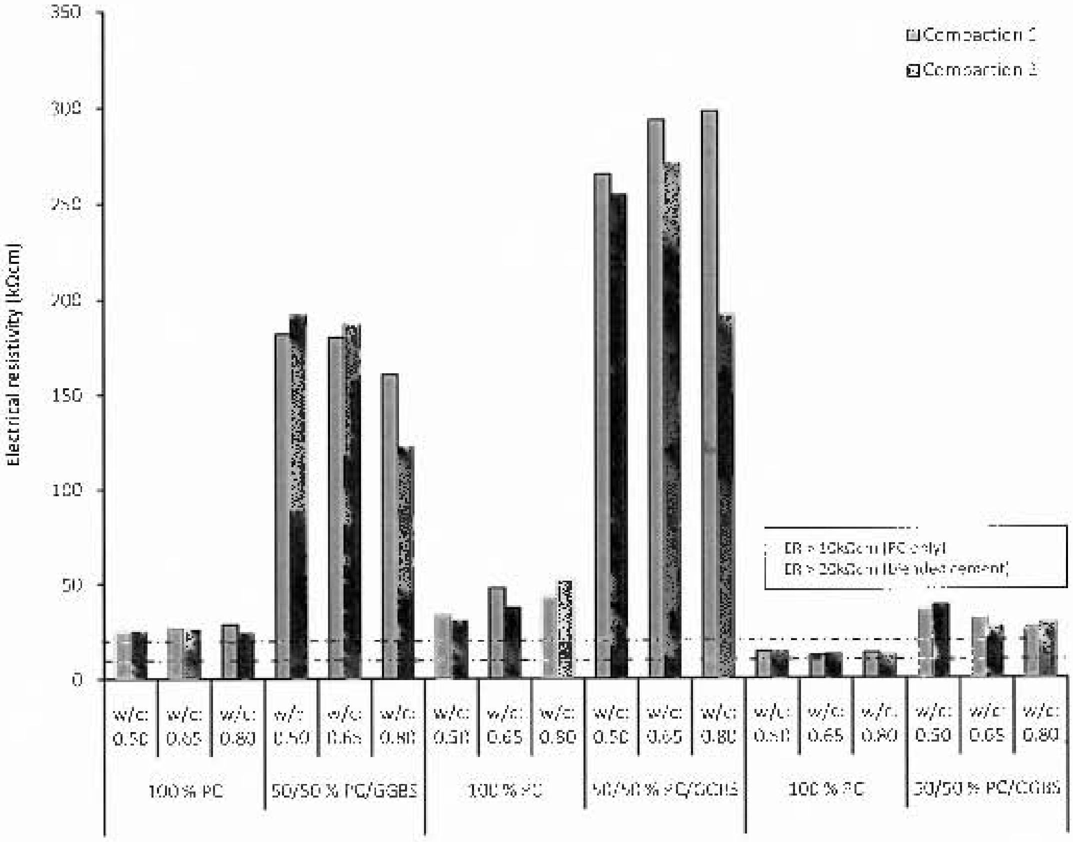


Figure 4.4: Overview of electrical resistivity results

It was found, that only at 40 days did both concrete types (50/50% PC/GGBS and 100% PC) meet the minimum electrical resistivity requirements. For this reason testing on winter samples was only initiated at 40 days. These electrical resistivity measurements are presented in Appendix D (Section 11.4).

(ii) Sensitivity of electrical resistivity test method to experimental variables

It is acknowledged that electrical resistivity is very sensitive to the addition of particular cement extenders, such as GGBS. Figure 4.4 shows that for an identical environmental exposure condition, the resistivity is appreciably higher for 50/50% PC/GGBS concretes than for 100% PC concretes. It is for this reason, that the current Swiss approach recommendations provide two limiting values depending on cement type:

1. 10 kΩ.cm for CEM I (viz. PC without reactive mineral additions)
2. 20 kΩ.cm for blended cements (e.g. PC with cement extender)

The electrical resistivity measurements are consistent with the expected moisture condition for each environmental exposure condition. Winter environment measurements are markedly lower than those for both summer conditions. In addition, the 90 day summer measurements are higher than those taken at 35 days, which is consistent with the drying expected as a result of being placed in the controlled environment (53 ± 2 % RH, 20 ± 2 °C).

The use of electrical resistivity to measure concrete moisture content was found to be valid. By looking at 50/50% PC/GGBS and 100% PC concretes separately, an increase in moisture content (for example by comparison of summer and winter environments) showed a corresponding decrease in electrical resistivity. The effectiveness of the specified limiting values and the subsequent influence of the moisture of gas-permeability, will be discussed in the sections to follow.

4.4.2 Electrical impedance (mass moisture)

Electrical impedance was used to measure the mass moisture (%) of each concrete sample. The instrument selected was the Tramex Elcometer CME4 moisture meter.

(i) Overview of electrical impedance results

Based on the Swiss recommendations for limiting moisture content (Section 2.7.1), all moisture requirements were met. For the summer condition this was expected, as the concretes would have not been exposed to moisture since being cast. This would allow sufficient time for moisture to be used in the hydration process, as well as for evaporation of the capillary water after hardening.

As described in Section 4.4.1., the winter samples were allowed to dry until the limiting moisture requirements were met. At 40 days all mean mass moisture requirements were achieved. It was on this basis that the concretes were deemed acceptable for testing. It was not deemed necessary for each individual measurement to meet the minimum requirement, largely due to the accuracy by which the instrument selected operates (i.e. ± 0.2 %). The mass moisture results for the winter condition are shown in Appendix D (Section 11.4).

An overview of the mass moisture measurements at the age of testing are shown in Figure 4.5.

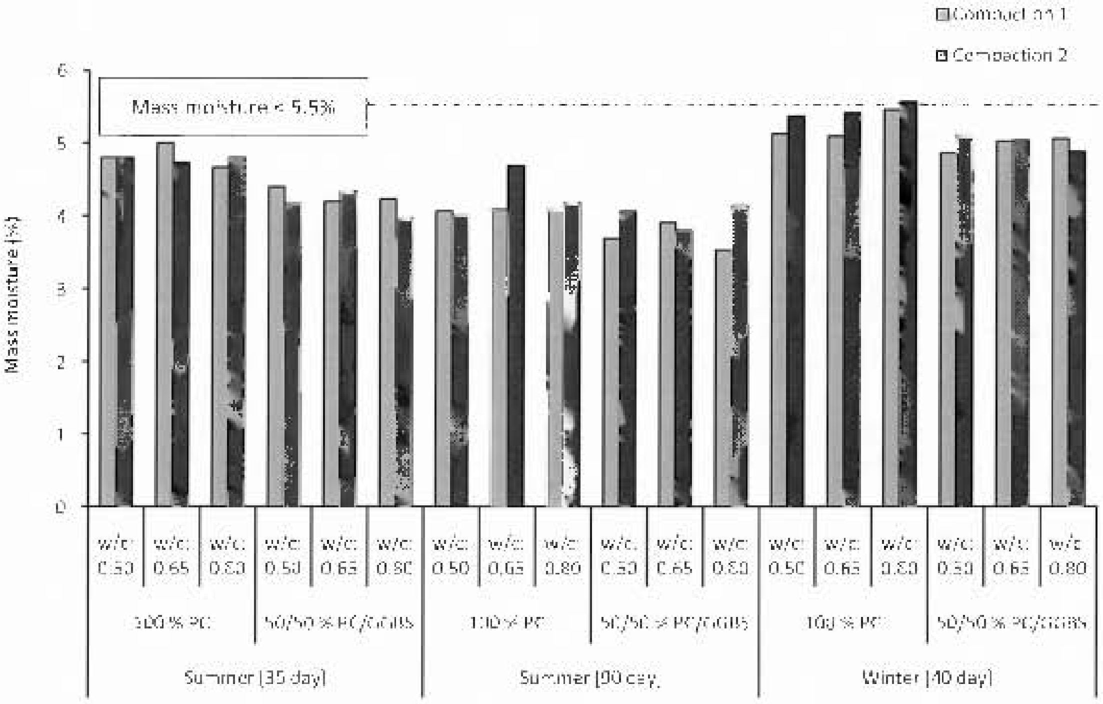


Figure 4.5: Overview of mass moisture results

(ii) Sensitivity of electrical impedance test method to experimental variables

In accordance with the current Swiss recommendations, the mass moisture (%) using electrical impedance should not exceed 5.5%. In comparison with the limiting values specified for electrical resistivity, the influence of cement type is not considered significant. However, Figure 4.5 shows generally lower mass moisture measurements for 50/50% PC/GGBS concretes, in comparison with that of 100% PC concretes. It is important to note, that while electrical resistivity (in accordance with the Swiss approach) is described independently for different cement types, it may in fact be a combination of (1) the cement types ability to hold moisture, and (2) the effect a particular cement composition on the electrical resistivity which will be measured. In essence, the relationship between cement type, moisture content and the moisture measurement cannot necessarily be inferred, based on the measurement techniques employed.

4.4.3 Comparison of moisture content measurement techniques

Dealing with moisture is not the focus of this study, however, literature has highlighted the importance of ensuring concrete is sufficiently dry when using gas-permeability based surface test methods (such as the Torrent method) to minimise the pore blocking effect of moisture. It was deemed necessary to perform a comparison of the recommended moisture measurement techniques, and to determine if either may be better suited for application in the integrated approach.

(i) Overview of moisture measurements

Figure 4.6 shows an overview of the electrical resistivity and mass moisture measurements for each environmental exposure condition, cement type and w/c ratio. The moisture measurements satisfied the requirements for moisture as currently specified by the Swiss approach guidelines. This has been discussed previously in Section 4.4.1 and 4.4 2.

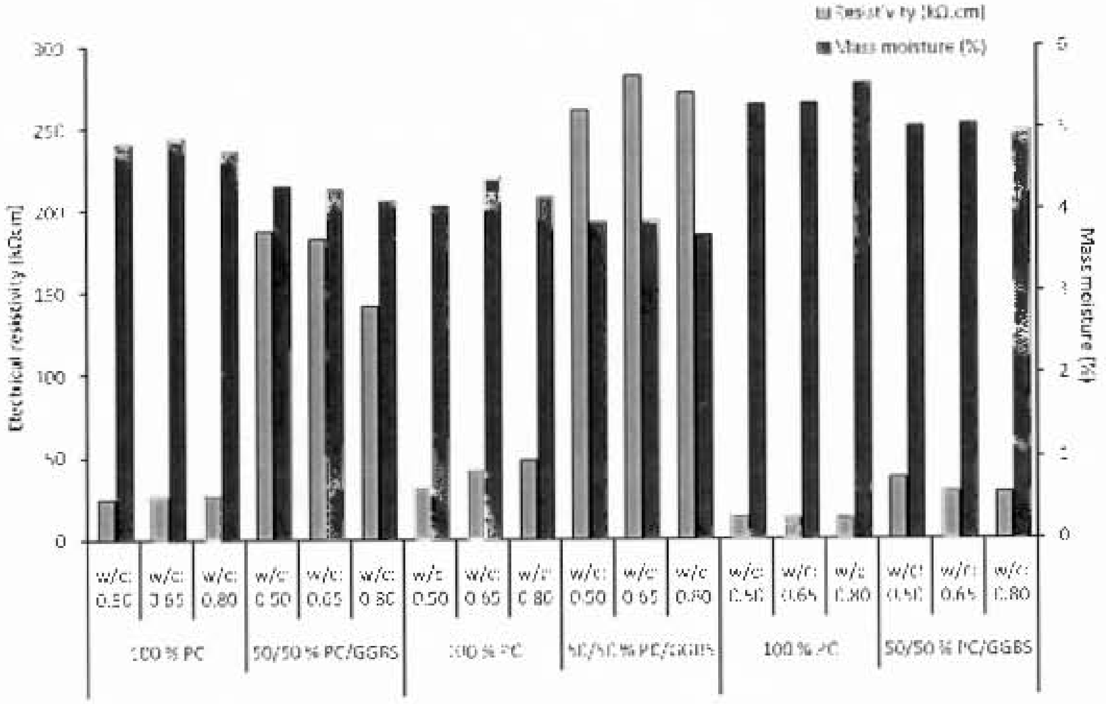


Figure 4.6: Overview of moisture measurements (Swiss approach)

(ii) Correlation between electrical resistivity and impedance measurements

It should be expected that due to the similarities between measurement instruments, and the sensitivity of these to common variables, a correlation between the two measurement techniques may be possible. Figure 4.7 shows this correlation, with data grouped according to environmental exposure condition and cement type. There is clear distinction between both environmental exposure and cement type.

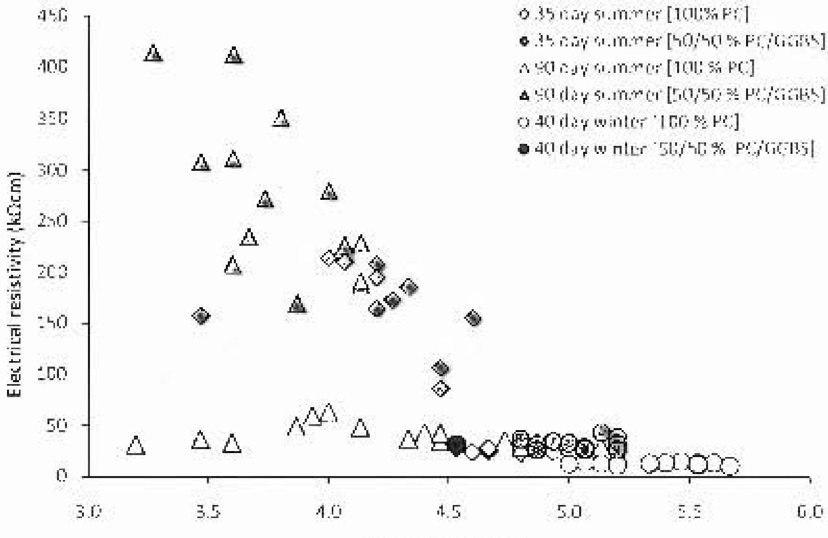


Figure 4.7: Correlation between electrical resistivity and mass moisture

The data is distorted by considerable scatter from both measurement techniques. Figure 4.8 provides a graphical display of the above-mentioned scatter. There is a clear a trend for 100% PC and 50/50% PC/GGBS concretes, however, the scatter suggests that a unique trend may in fact not be valid.

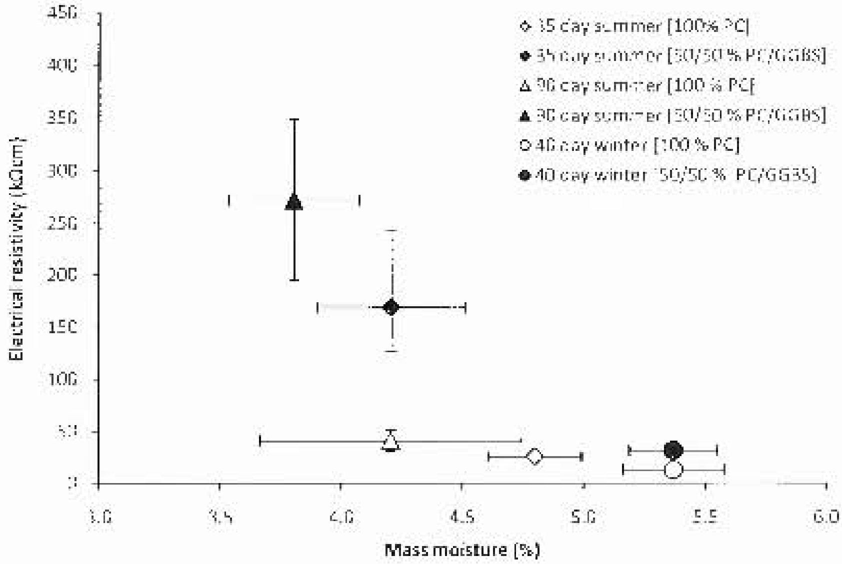


Figure 4.8: Moisture correlation showing mean and standard deviation

4.4.4 General observations from moisture content assessment

Based on the results presented, the following observations are made:

- Electrical resistivity is highly sensitive to cement type, with the addition of cement extenders (such as GGBS) resulting in considerably higher measurements.

- Mass moisture measurements appeared sensitive to the addition of GGBS as a cement extender. However, cement extender addition results in a very small mass moisture difference, but a large electrical resistivity difference.
- The correlation between mass moisture and electrical resistivity measurements exists with a high degree of scatter. However, cement type is clearly distinguished by both methods (in particular by electrical resistivity).
- Electrical resistivity and mass moisture limiting values (in accordance with the Swiss approach) were found to be comparable. The validity of these limiting values (by assessing the influence of gas-permeability) will be discussed in the sections to follow.
- From a relatively moist state, the winter samples required 5 days to meet the minimum limiting moisture values. This may suggest 2-5 days (as recommended by the Swiss approach) is not adequate, and should be increased to at least 5 days without exposure to moisture at the surface.

4.5 Comparison of OPI and Torrent gas-permeation results

The focus of this study was to establish a correlation between two permeability-based tests methods, namely, the OPI test and Torrent method. In this section, the correlation is presented and evaluated critically. A few proposals are made for the use of this correlation to improve the DI approach. Some general observations which provide further insight into the relationship between density, compaction, strength and gas-permeability results are provided in Appendix D (Section 11.3).

4.5.1 Effect of test variables on gas-permeation results

The OPI test and Torrent method were found to be highly sensitive to intrinsic (cement type, w/c ratio) and extrinsic (environmental exposure) factors. Intrinsic experimental methods were controlled by material specification. However, extrinsic methods (e.g. compaction) were somewhat less conventional. Environmental exposure conditions were chosen to simulate typical conditions in South Africa during dry (summer) and wet (winter) months in the year. Further, the degree of compaction was achieved through the use of a systematic (albeit unconventional) method. Due to the absence of any standardised method for manipulating the degree of compaction, a method was developed, although, results obtained were found to be highly variable not as expected. For this reason, the mean value across compaction methods is presented in Figure 4.9. Figure 4.9 shows an overview of the gas-permeability measurements using the OPI test and Torrent method.

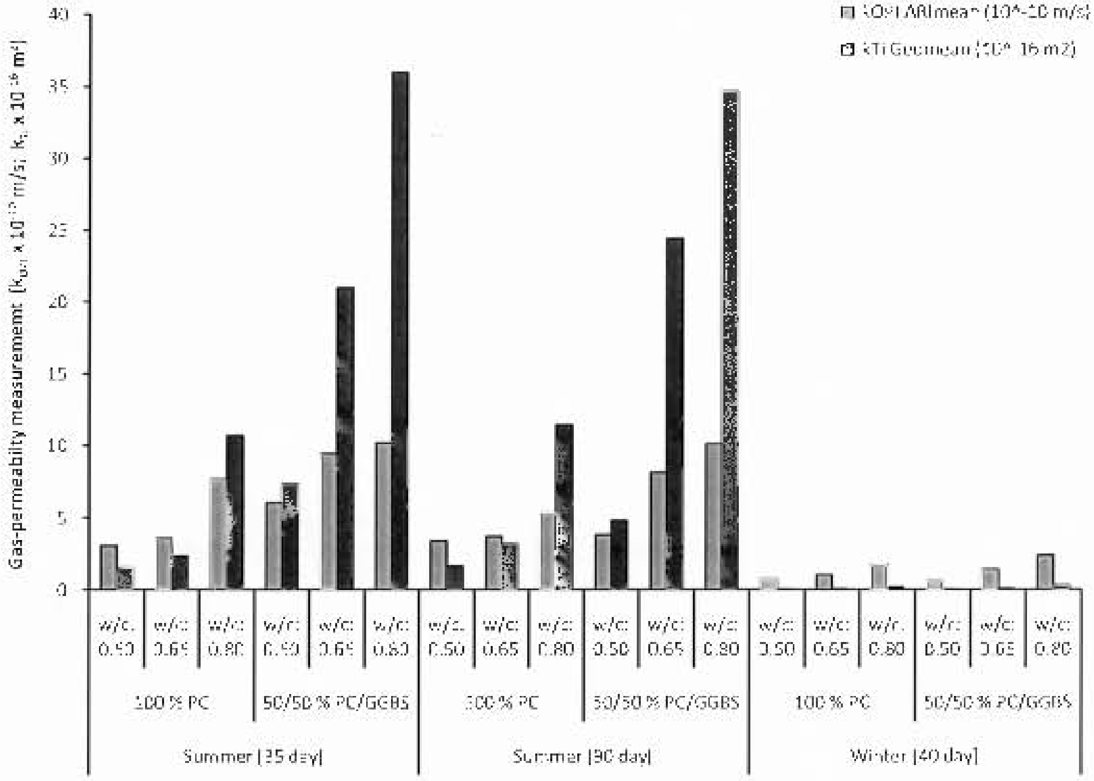


Figure 4.9: Overview of OPI test and Torrent method results

(i) Cement type

Both OPI test and Torrent method showed clear distinction between 100% PC and 50/50% PC/GGBS concretes. In particular, the addition of cement extender GGBS resulted in an appreciable increase in gas-permeability in the summer environmental exposure conditions, due to the dependence of GGBS (a latent hydraulic binder) on available moisture for curing. The importance of good quality curing was evident by the large discrepancy between summer and winter 100% PC and 50/50% PC/GGBS concretes for both permeability test methods. As mentioned previously, careful attention should be paid to all discussions regarding low Torrent permeability values (due to the magnitude of permeability classes), to ensure that these are not interpreted erroneously.

(ii) w/c ratio

For w/c ratios 0.50, 0.65 and 0.80, the OPI test and Torrent method showed clear distinction. This was expected, as a lower w/c ratio is known to produce concretes of generally lower permeability given adequate curing and compaction. The w/c ratio was identified as one of the main controlling parameters for gas-permeability in this study.

(iii) Compaction

It is expected that a higher degree of compaction should result in a denser hardened concrete, and hence a lower gas-permeability. This is difficult to control, as compaction is dependent on sample size, concrete mix consistency and material selection. However, the experimental procedure developed used a systematic method (termed the 'drop' test) which was primarily used to investigate whether the correlation would be sensitive to the efficiency of compaction. The results suggest that the method used to achieve poor compaction was not successful, resulting in varied results with no clear trend. For this reason, compaction methods were referred to as only methods 1 and 2. However, it was found that both test methods used were able to identify the different levels of compaction, even though the level of compaction itself was not as expected. In particular, it was identified that the combined effect on compaction and curing may require further investigation.

(iv) Environmental exposure

In order to simulate typical environmental conditions in South Africa, samples were placed in 'summer' and 'winter' environments (these have been explained previously). Samples were tested at 35 - 40 days, showing a considerable reduction of gas-permeability for both 100% PC and 50/50% PC/GGBS winter concretes. The 50/50% PC/GGBS concretes were greatly affected by the lack of moisture available in the summer condition (in comparison with the 100% PC concretes).

It was concluded that the permeability of concretes tested using the OPI test may (to a large extent) eliminate the effect of moisture as a result of the preconditioning required. However, the Torrent method measurement gives an indication of the combined effect of environmental exposure (curing) and moisture content at the time of testing. The moisture effect is well documented in literature, however, means for correcting gas-permeability measurements are less established.

The lack of moisture availability (i.e. poor curing) at early ages has a detrimental effect on the gas-permeability of a concrete in its hardened state. This was clearly identified by both Torrent method and OPI test. The effect was emphasised for concretes where 50/50% PC/GGBS concretes were used, as discussed previously.

(v) Testing age

As concrete ages (under typical conditions), so the hydration process should result in reduced concrete permeability. The rate of hydration decreases exponentially with increasing age, which suggests that at some point the concrete will experience no further hydration. At 35 days, 100% PC concrete would have reached a higher degree of hydration than for the 50/50% PC/GGBS concrete, and hence the reduction in permeability (with increasing age) is more pronounced for the 50/50% PC/GGBS concretes.

It should be noted, however, that drying is expected for the summer concrete as age increases. The reduction in moisture content has no effect on the OPI test (due to preconditioning), however, it is expected that the Torrent method may also be affected by the pore blocking effect of moisture (even for particularly dry concretes). The Torrent gas-permeability is expected to decrease due to increased hydration (improved concrete quality), and also increase due to the reduction in the pore water of concrete samples stored in a 'dry' controlled environment. The more prevalent of these will control the net effect on gas-permeability. By comparison of the results from both OPI test and Torrent method, it was concluded that from 35 days and 90 days in the summer environment, evaporation of pore water has a greater influence than the reduction of gas-permeability due to hydration.

Testing age appeared to have an appreciable effect on the blended concrete, highlighted by the OPI test only. The Torrent method showed a similar trend, however, it was not conclusive. This was due to the uncertainty surrounding moisture in the concrete at the time of testing.

4.5.2 Correlation between OPI test and Torrent method

Figures 4.10 and 4.11 show the correlation between OPI test and Torrent method for the complete data set. It was found that a power function equation achieves a good fit ($R^2 = 0.95$). The power function is shown in Equation 4.1.

$$k_{Ti} = 0.0341\, k_{OPI}{}^{3.0296} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

where: k_{Ti} = k-value from the Torrent method (x 10^{-10} m/s)

k_{OPI} = k-value from the OPI test (x 10^{-16} m^2)

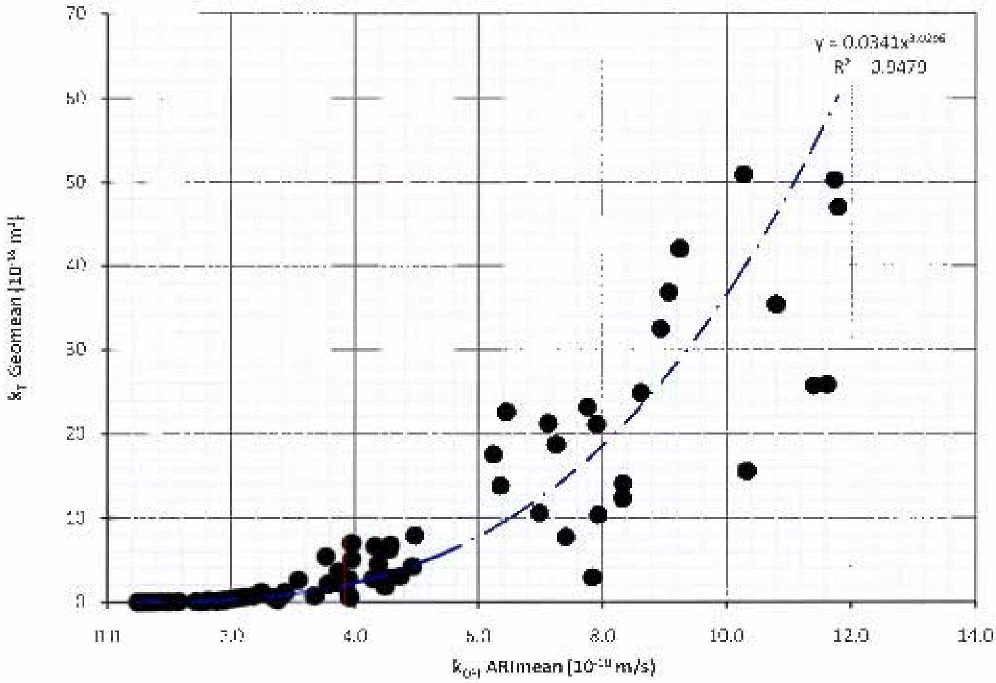


Figure 4.10: Correlation between k_{OPI} and k_{Ti} complete data set

The power function correlation shown in Figure 4.10, may also be presented as a straight line on log-log axes. This is shown in Figure 4.11. This is of particular importance, as it confirms the findings from previous researchers (Section 2.9). Further, the log scale also provides a more clear presentation of the vast range of permeability data (in particular for the Torrent method, viz. k_T from 0.001 to 100).

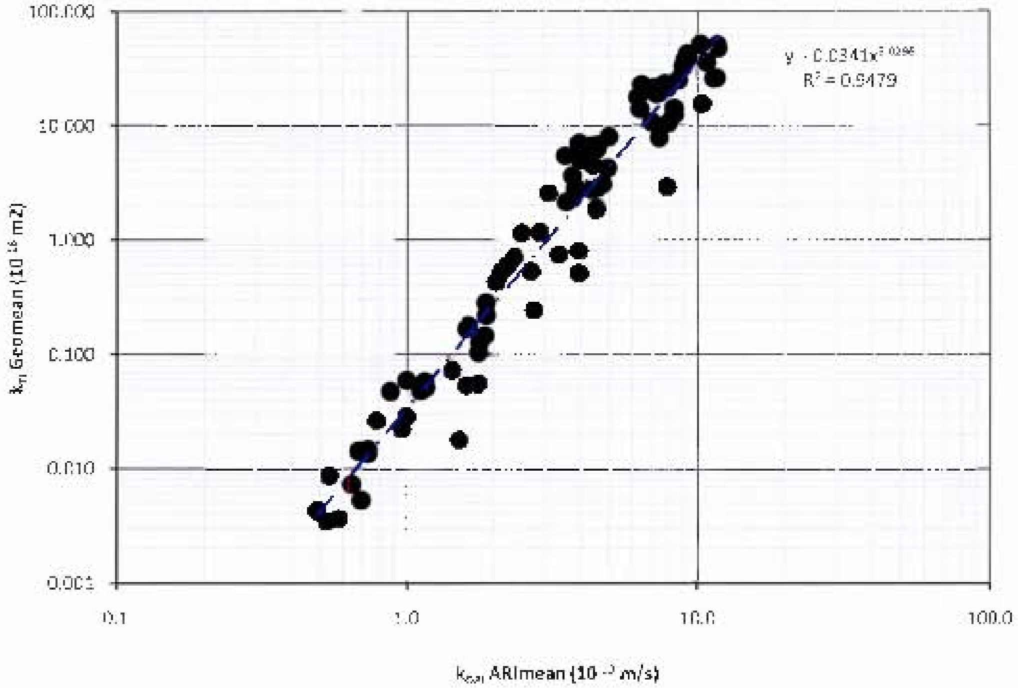


Figure 4.11: Correlation between k_{OPI} and k_{TI} complete data set (logarithmic)

The OPI test measurement is commonly represented by the OPI (-) value, as this is easier to use for practical application. The OPI value usually lies between 9 and 11, and is calculated in accordance with Equation 2.22. Figure 4.12 shows the correlation between OPI and log (k_{Ti}), again showing a straight line for the power function. The OPI axis provides a good indication of the wide range of permeability data achieved through this study. Table 2.4 (Chapter 2) classifies the OPI data in this study from very poor to excellent in terms of durability classes.

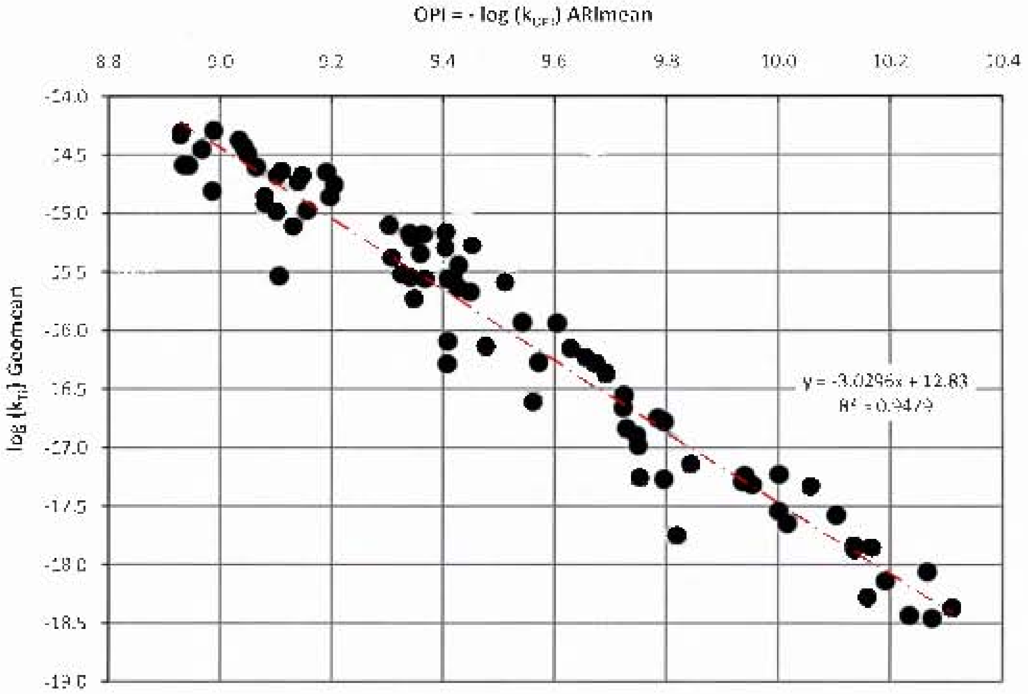


Figure 4.12: Correlation between OPI and log (k_{TI})

4.5.3 Classification criteria for gas-permeation results

In research by EMPA (2006), the classification criteria for Torrent method and OPI test were compared in order to provide an indication of the conclusions to be drawn from each method, tested on identical concretes. A slight disparity between permeability classes from OPI and Torrent methods was shown, with classification according to the Torrent method (in comparison with the OPI test), being more 'pessimistic' with regards to the outcome of the concrete durability.

Figure 4.13 provides an illustration (logarithmic scale) of the comparability of classification criteria for Torrent method and OPI test. It can be seen that the data generally fits inside the region of corresponding categories. This provides further support for the integration of the two gas-permeability-based test methods.

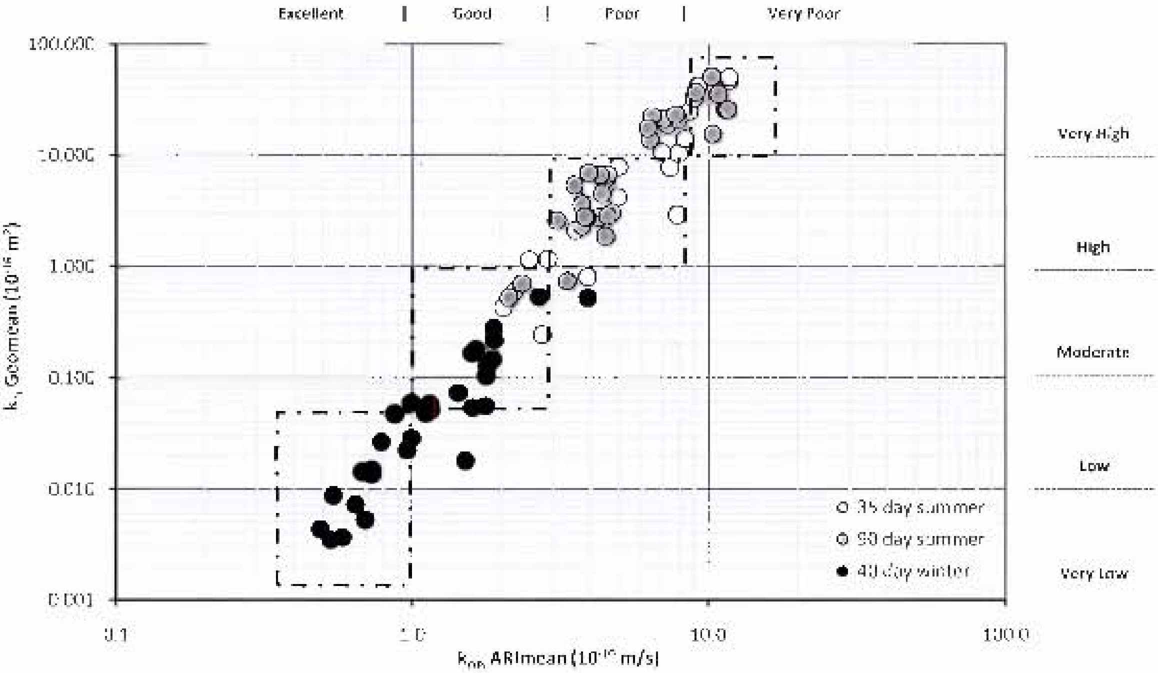


Figure 4.13: Classification criteria for complete data set (logarithmic)

4.5.4 Moisture correction for proposed performance-based specification

The influence of moisture on the Torrent method has been discussed in detail (Section 2.7). An important observation was the apparent influence of moisture content at the time of testing, for each of the environmental exposure conditions. Two methods have been specified by the Swiss approach (Torrent et al., 2012) for limiting moisture content, namely, by the use of electrical resistivity or electrical impedance.

In this study, two approaches are proposed in order to account for the influence of moisture. The first approach is a more simplistic approach, while the second approach (using multiple linear regression) considerably more complex. It should be noted that these are presented as forward thinking approaches, however, if the moisture content meets the Swiss approach requirements it appears that the influence of moisture on gas-permeability is minimal. For this reason, a more generalised equation, which accounts for the uncertainty linked to moisture influence by means of a statistical range is presented in Section 4.5.5.

The moisture content (measured using electrical impedance) for each environmental exposure condition is shown in Figure 4.14.

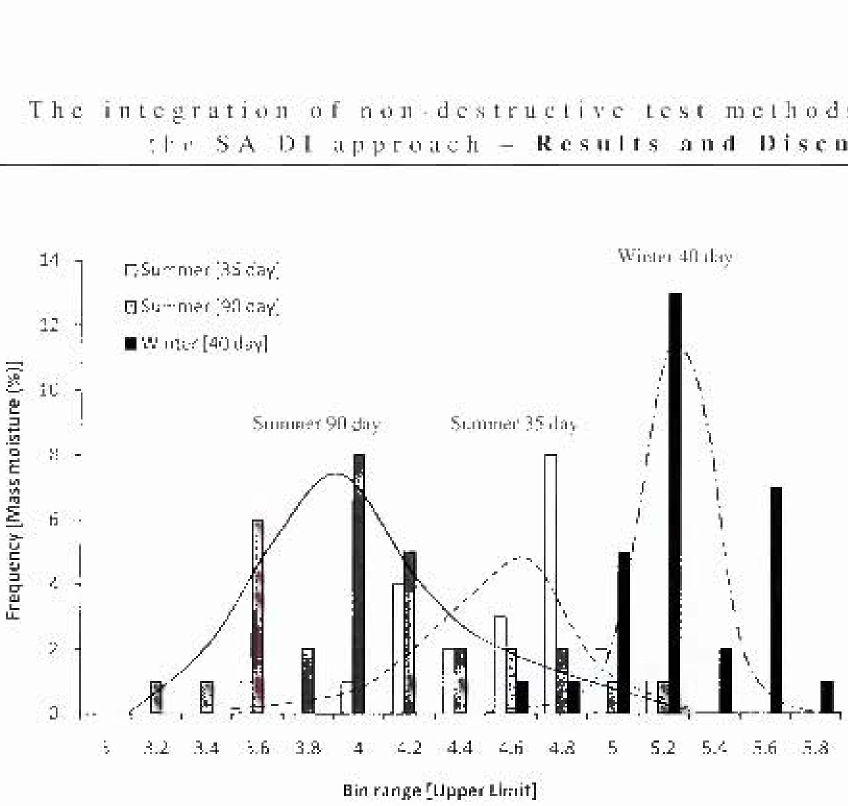


Figure 4.14: Environmental exposure moisture content histogram

The mean moisture content (measured using electrical impedance) for the winter environment (40 days) was 5.2 %; summer environment (35 days) was 4.5 %; and summer environment (90 days) 4.0 %. The winter environment had the highest moisture content due to the periodic ingress of water by environmental exposure. The drying which took place between 35 and 90 days on summer samples is evident, with these samples being kept in a controlled environment with no additional water ingress.

(i) Simplistic approach for moisture correction

The simplistic approach is based on the assumption that it is only the moisture content at testing which varies between otherwise identical concretes. As described in Section 4.5.2., the data is best fitted by a power function of the general form displayed in Equation 4.2.

$$k_{Ti} = a.k_{OPI}{}^{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

where: k_{Ti} – k-value from the Torrent method (x 10^{-10} m/s)

k_{OPI} – k value from the OPI test (x 10^{-16} m^2)

The effect of moisture (on the Torrent method) therefore results in an apparent shift in the direction reduced moisture content along the k_{Ti} axis. As shown in Figure 4.16, an increased moisture content results in a vertical downward shift of the correlation on log-log axes, which is dependent on both *a* and *b* variables. It should be noted that the effect of moisture is exponentially greater for higher permeability concretes, as shown in Figure 4.15.

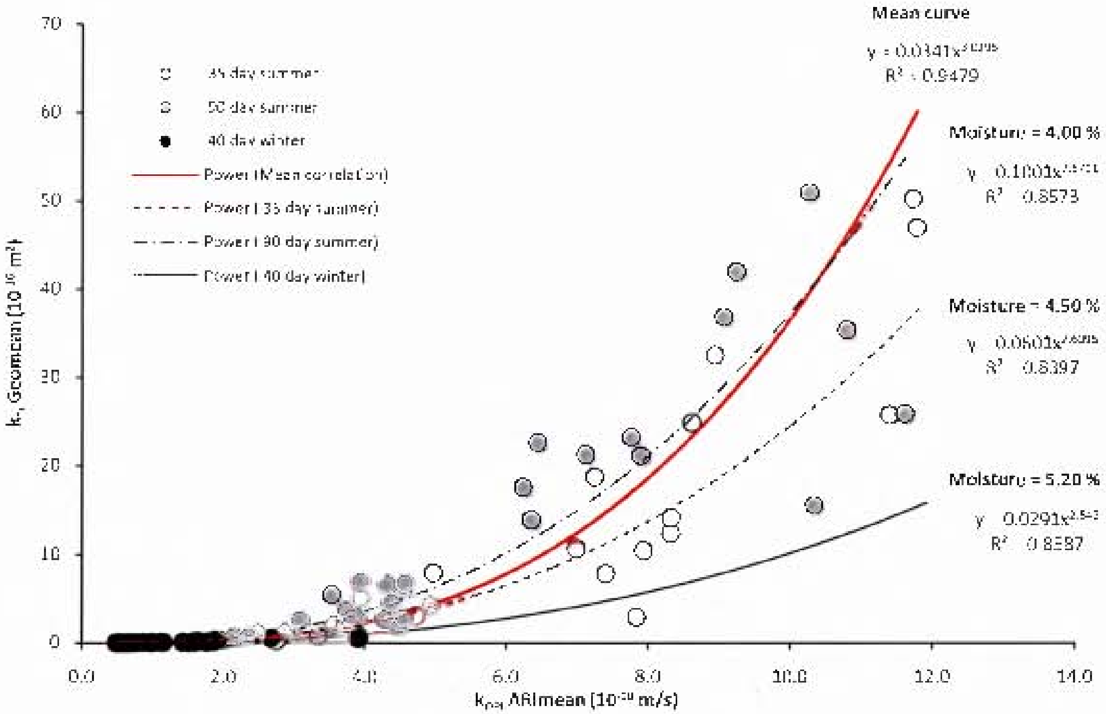


Figure 4.15: Simplistic approach for moisture correction

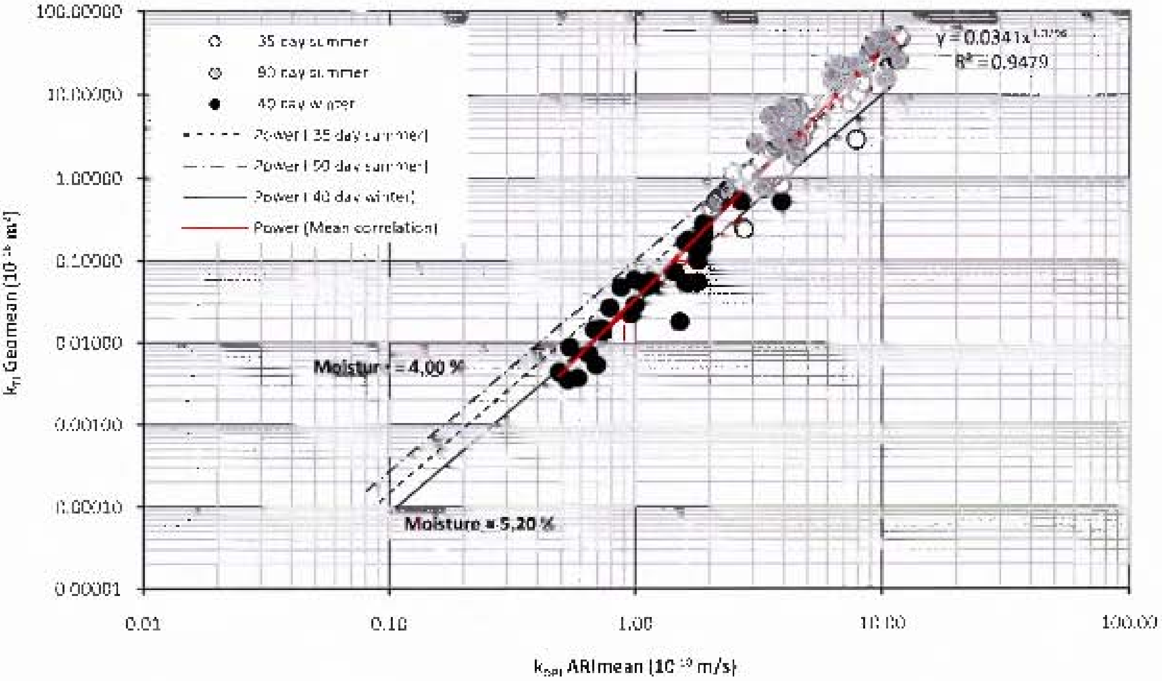


Figure 4.16: Simplistic approach for moisture correction (logarithmic)

The simplistic approach allows for an adjustment based on the mean mass moisture measured using electrical impedance. It is recommended that Figure 4.15 be used for higher permeability concretes (viz. $k_{TI} > 10 \times 10^{-16}$ m²), while Figure 4.16 be used for lower permeability concretes (viz. $k_{Ti} < 10 \text{ x } 10^{-16}$ m^2). This is advised due to the scaling of these figures. The mean correlation line is also shown, providing important insight into the selection of moisture correction curve. For low permeability's, the mean line appears closely approximated by the 5.2% moisture curve, while for higher permeability's the mean line appears better approximated by the 4.0% moisture curve. It should also be noted that the 5.2% moisture curve becomes a particularly poor approximation at higher permeability's, and may be quite misleading to the engineer performing the assessment. This discussion may suggest that, given more data and a set of verification testing, a unique curve for high and low permeability concretes may provide a more acceptable representation of the data.

The aim of the simplistic approach is to provide the possibility for moisture correction of the correlation curve, however, the outcome of the permeability classification is not expected to change as a result of the moisture correction (provided the moisture measurement satisfies the Swiss approach recommendations by mass moisture or electrical resistivity. This may not be true when investigating particularly poor quality (or high permeability) concretes.

(ii) Multiple linear regression for moisture correction

Multiple linear regressions allow us to describe a single dependent variable in terms of two independent variables (Alder & Roessler, 1976). The general form for linear regression using two independent variables is shown in Equation 4.3.

$$Z = a + bX + cY \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.3)$$

where: a, b and c = Constants found using the method of least squares

X and Y = Independent variables

A summary of the method used to perform multiple linear regression is presented in Appendix D (Section 11.5). The general equation for the multiple linear regression is shown in Equation 4.4. The scatter has been reduced significantly by the inclusion of moisture as a second independent variable.

$$\ln(k_{OPI}) = 0.763 + 0.326.\ln(k_{Ti}) + 0.077\,.m\% \quad \ldots\ldots\ldots\ldots \quad (4.4)$$

where: k_{Ti} = k-value from the Torrent method (x 10^{-10} m/s)

k_{OPI} = k-value from the OPI test (x 10^{-16} m^2)

$m\%$ = Mass moisture using electrical impedance (%)

Equation 4.4 provides an equation which describes the multiple linear regression for the correlation between OPI test and Torrent method permeability. By comparison with the regression from Section 4.5.2., the scatter has been markedly reduced. It can be seen that the influence of moisture is relatively small (with *m%* usually in range of 3 to 5 %). Figures 4.17 and 4.18 show the original correlation (Equation 4.1), as well as that estimated by Equation 4.4. In reality, the regression coefficient (R^2) for the multiple linear regression is only marginally improved from $R^2 = 0.948$ to 0.949.

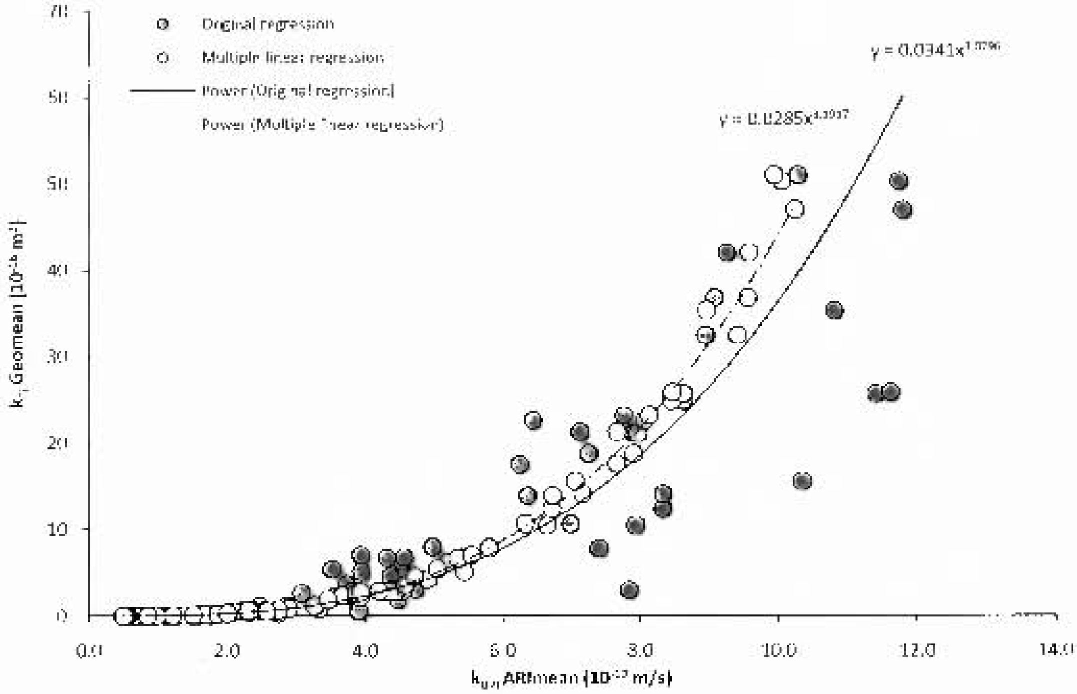


Figure 4.17: Multiple linear regression for moisture correction

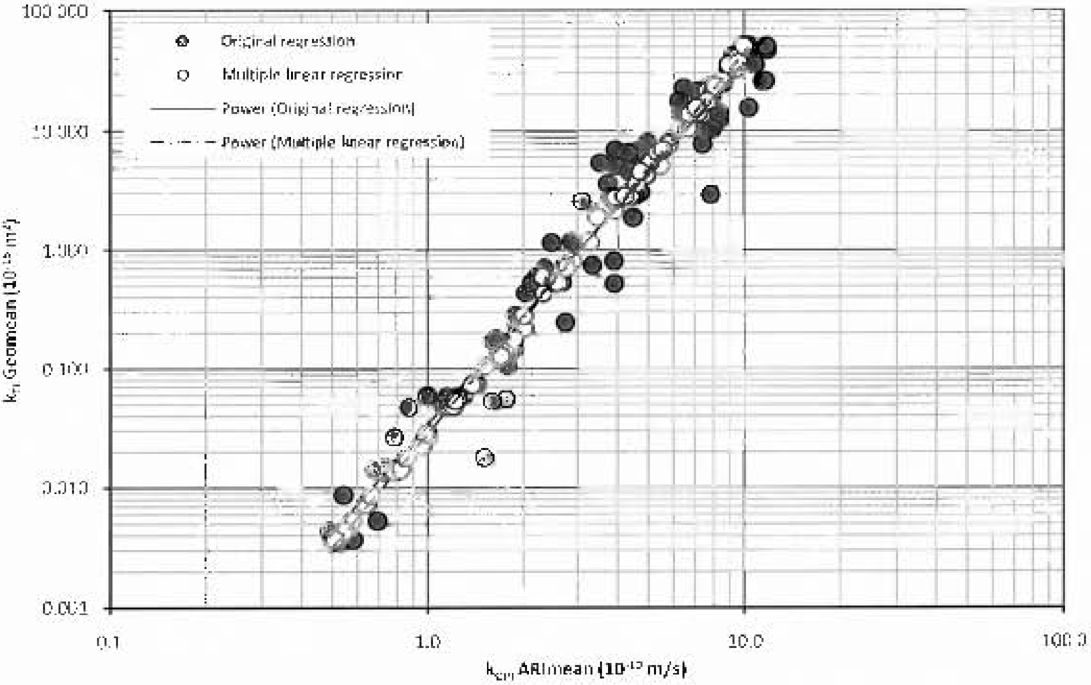


Figure 4.18: Multiple linear regression for moisture correction (logarithmic)

4.5.5 Proposed performance-based specification

A few different methods for interpretation of the data have been presented. Based on the small influence of moisture on the correlation, the proposed performance-based specification assumes this effect negligible (if within the Swiss approach specifications). Although multiple linear regression presents with far less scatter (than the original correlation), it is not possible to test the accuracy of this correlation without performing further tests using both test methods. Verification is proposed in order to test the accuracy of the multiple linear regression presented (Section 4.5.4 (ii)).

The proposed specification aims to account for the scatter of the original correlation (Section 4.5.2), by employing a limiting curve within which 'most' of the experimental data should fall. The method used to develop this limiting curve was somewhat unconventional, as it was required to fit a power function closely for values of magnitude 0.0001 to 100 (six orders of magnitude). Figure 4.19 shows the mean value and standard deviation for environmental exposure condition and cement type (neglecting the effect of moisture).

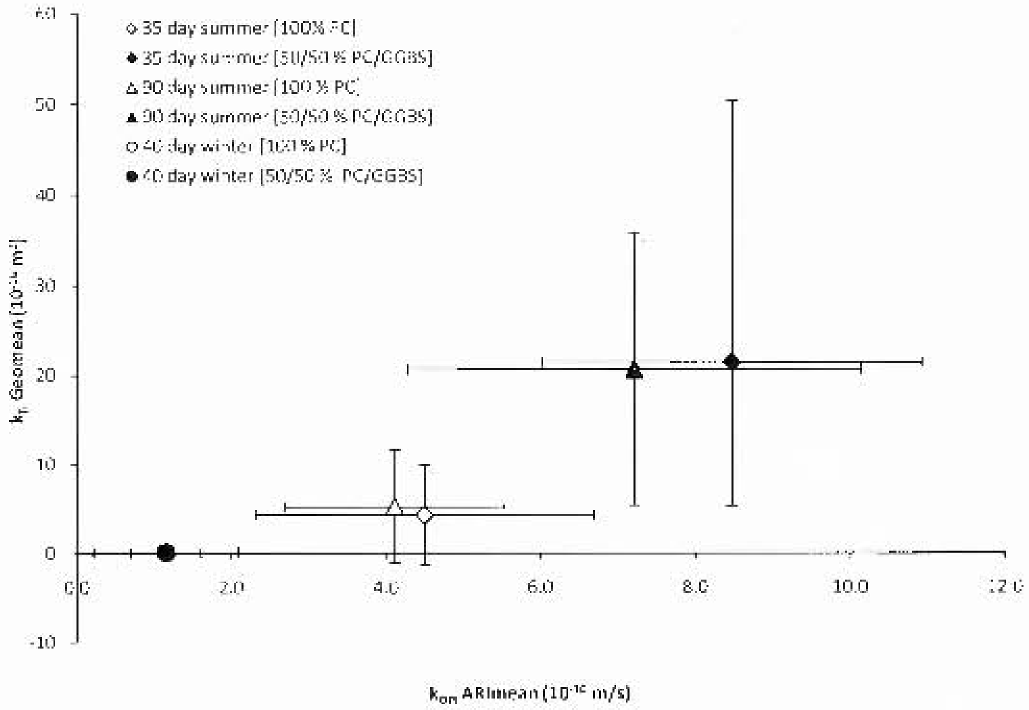


Figure 4.19: Correlation between k_{OPI} and k_{T} standard deviation plot

The experimental data was grouped into categories of bandwidth OPI = 0.20, for data in the range 8.8 < OPI <10. For each category, the mean value, standard deviation, standard error and range were investigated. Categorization was necessary in order to provide reasonable statistics over such a wide range of permeability data (6 orders of magnitude). In particular, it was found that if the data was treated as a single sample set, the statistical tools became insensitive to the regions of low permeability.

It was found that for each category (as selected), the standard error and standard deviation values were similar. Figures 4.20 and 4.21 show (using categorisation) the mean regression line, as well as a boundary line based on one standard error (or approximately one standard deviation) and the limiting (maximum or minimum) range.

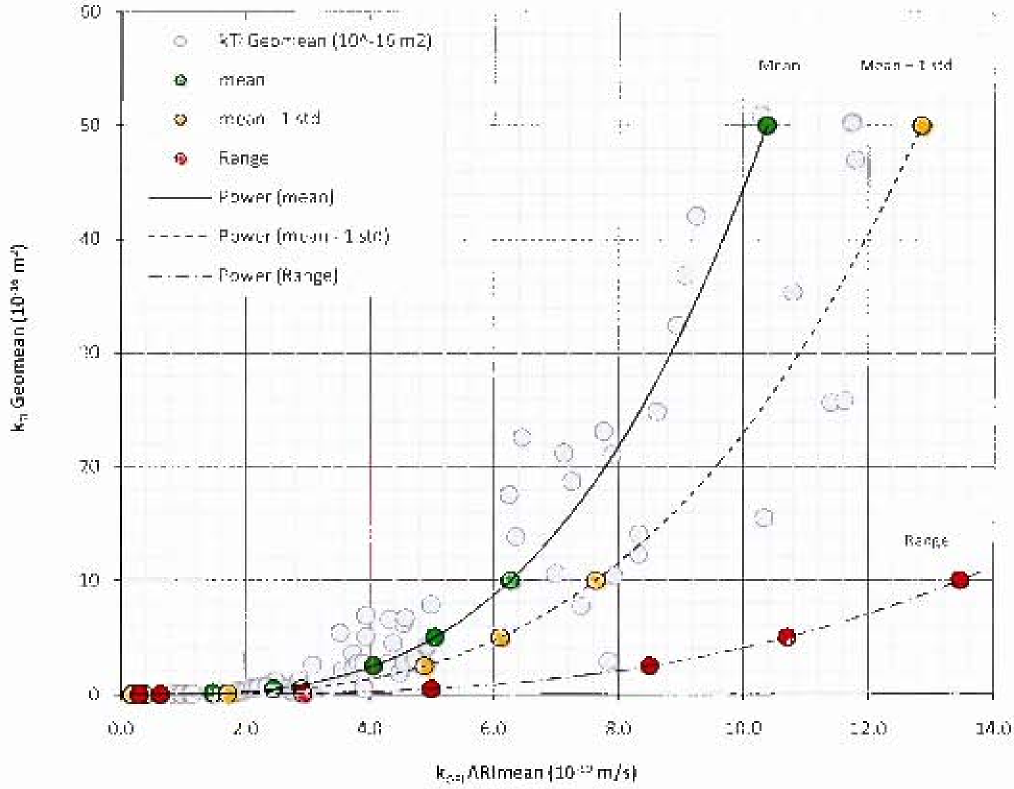


Figure 4.20: Correlation between k_{OPI} and k_{Ti} showing limiting curves

As mentioned above, it should not be expected that the mean curve shown in Figures 4.10 and 4.11 will be identical to that of Figures 4.20 and 4.21. This is due to method used for categorization of the permeability data.

Figures 4.20 and 4.21 may be used to provide an indication of the k_{OPI} value expected for a measured k_{Ti} value. It was deemed adequate to provide a curve which (with a given level of certainty) provides a 'worst' case k_{OPI} value for a given k_{Ti} value. The range is based on the outmost data points from each category, while the standard deviation is based on the mean value minus one standard deviation (which yields a similar result to the mean value minus one standard error).

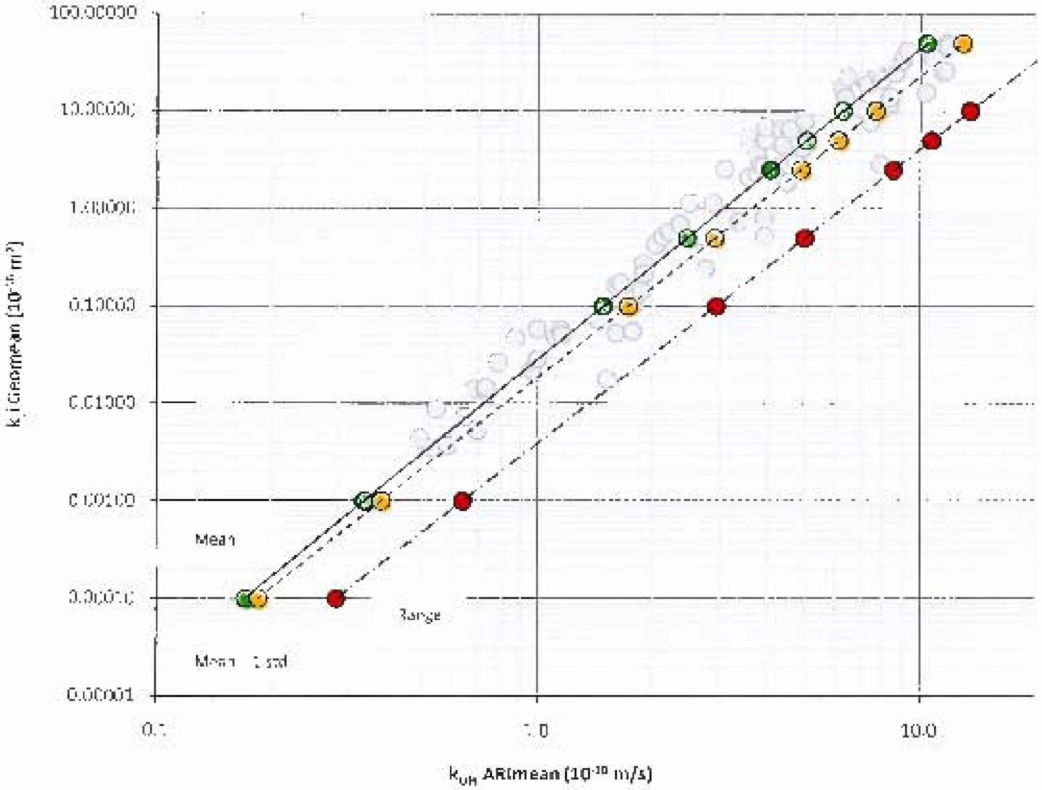


Figure 4.21: Correlation between k_{OPI} and k_{Ti} showing limiting curves (logarithmic)

On this basis, it can be seen that for a measured k_{Ti} value, the 'worst' k_{OPI} value expected may be determined using the 'range' curve. It should be noted that this curve (for most conditions) may be considered too conservative for practical application. In addition, for a measured k_{Ti} value, it is 'unlikely' that the k_{OPI} value would exceed one standard deviation from the mean. Figures 4.20 and 4.21 may be used to assess the probability with which the k_{OPI} value predicted would be an underestimation of the true (or measured) value.

4.5.6 Summary

The results presented above show a correlation between two permeability-based tests methods, namely, the oxygen permeability index test and Torrent method. The results fit well within the envelope of expected values according to the permeability classification criteria for each method. A general correlation is presented, describing the implications of a power function regression. The influence of moisture on the k_{Ti} measurement is evident, and two alternative methods for correcting the correlation are presented. Due to the relatively small influence of moisture on the correlation (provided the moisture recommendations in the Swiss approach are met), a final performance-based specification is proposed. This specification aims to improve the confidence with which the correlation may be adopted, by providing a statistical 'worst case' correlation curve.

4.6 Comparison of previous and current experimental results

In the preceding sections (4.2 - 4.5), only the experimental data from this study has been presented. This is due to the discrepancy between results from different researchers. This is discussed below.

4.6.1 Previous studies versus current experimental results

In this study, the experimental work was carried out using a systematic methodology. The experimental methodology was developed to ensure a wide range of permeability values were achieved, greater than achieved by previous researchers. Subsequently, it has been found that the results present a high degree of consistency. In addition, the moisture content at testing has been used to present a possible correction to further reduce the scatter of the correlation in the future (Section 4.5.4 (ii)).

Previous studies have resulted in a number of trends between k_{OPI} and k_{Ti}, however, these have also resulted in markedly low correlation coefficients. The experimental methods have been described in Section 2.9. Figures 4.22 and 4.23 show a compilation of the trends from all previous (and current) studies.

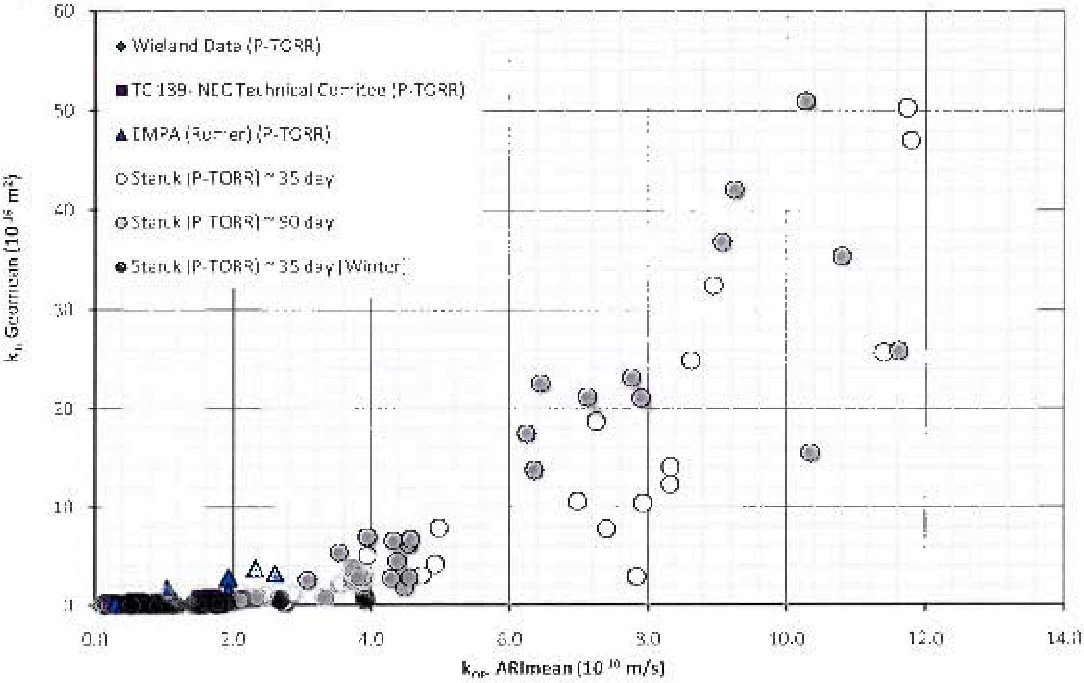


Figure 4.22: Existing research versus current study correlation

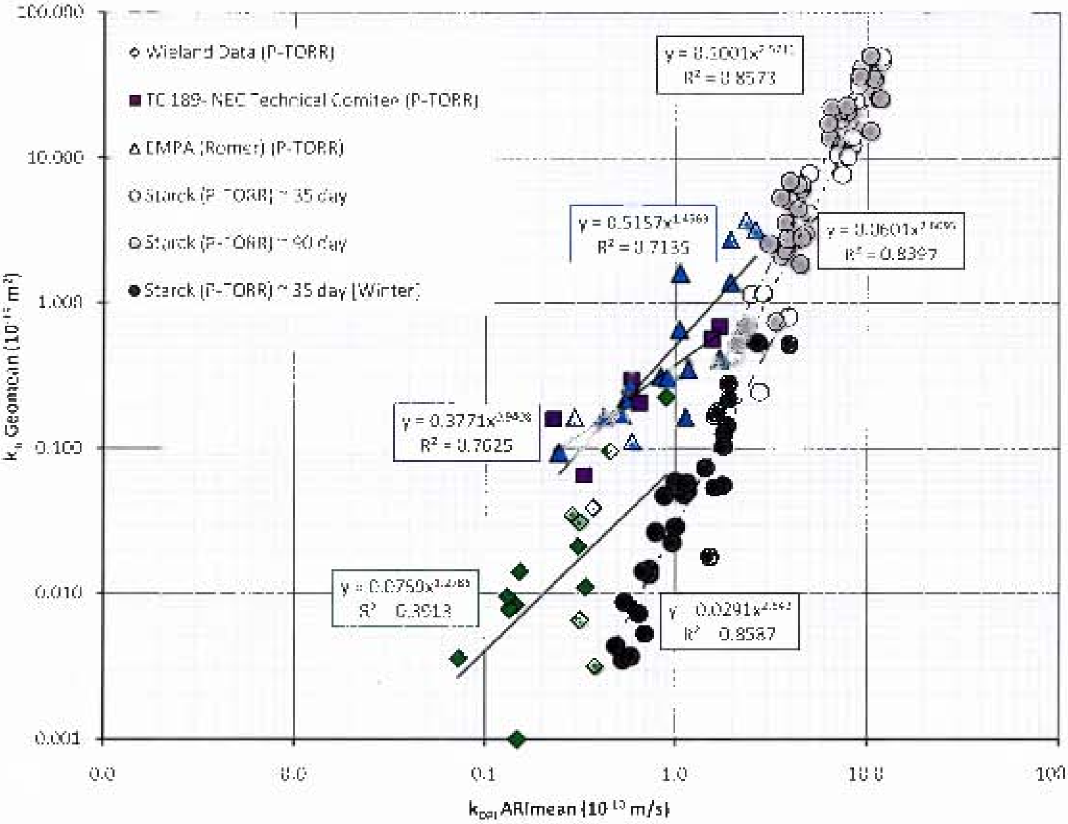


Figure 4.23: Existing research versus current study correlation (logarithmic)

4.6.2 Discussion of experimental methods and results

Research performed in this study appears to be fit well with an exponential power function. Further, the data spans a large range of permeability data, with a high correlation coefficient ($R^2 = 0.83$ to 0.86) for each environmental exposure condition.

In research performed by Wieland (2009), the range of permeability values were very low. Further, the correlation coefficient was particularly poor ($R^2 = 0.39$). The EMPA (2006) research was performed using an unconventional experimental methodology. In particular, the effects of temperature and moisture were investigated for very low relative humidity's. Further, the test conditions were not explicitly documented, making it difficult to critique the results obtained. In the research performed by RILEM TC 189-NEC (2005), the sample size was particularly small (6 samples), which may lead to a misleading representation of the correlation. For both EMPA and RILEM TC 189-NEC studies, the OPI test specimens were cored and dried before transporting to the testing laboratory. This resulted in a time delay between coring and testing of the OPI samples, which could have led to further hydration taking place in the interim.

These areas of uncertainty suggest that some variables, which may have not been investigated in study, may in fact strongly affect the correlation between k_{OPI} and k_T. On this basis, further research into the effect of material selection (e.g. coarse aggregate maximum size and type) may be suggested to adjust or verify the correlation presented in this study.

4.7 Summary

The oxygen permeability index (OPI) test and Torrent method have been shown to be sensitive to the most common concrete factors. These include intrinsic factors (w/c ratio, cement type) and extrinsic concrete factors (curing). The moisture measurement techniques (as presented in the Swiss approach) have been found adequate in order to minimise the 'pore blocking' effect of moisture on concrete permeability. Two methods have been presented in order to account for the moisture content in concrete, the first being a simplistic approach, and the second method being developed using a multiple linear regression of the k_{OPI} versus k_{Ti} data.

The final correlation (neglecting the effect of moisture on k_{Ti}) has been presented with a 'worst case' limiting curve. This line aims to ensure that for a particular k_{Ti} measurement, there is a high probability that the corresponding k_{OPI} value would be lower (less permeable) than that predicted using the mean values. In this way, a degree of statistical confidence is enforced.

In a comparison with previous studies, the data is best fitted with an exponential power function ($R^2 = 0.83$ to 0.86) for each environmental exposure condition. For each exposure environment, the range of permeability data is considerably higher than that presented by previous researchers, and consisting of larger sample sizes. The discrepancy between previous studies and current research are not completely understood, and may be attributed to differences in experimental methodology or material selection.

CHAPTER 5

5 INTEGRATED APPROACH FRAMEWORK

5.1 Introduction

The aim of this study was to present an opportunity for improvement of the South African Durability Index approach, to include the supplementary use of Torrent method. This was investigated experimentally, and the results showed good potential the use of a gas-permeability correlation for improvement of the DI approach. The limitations of such an integration should also be considered, in particular the effect of moisture on the correlation. This chapter presents the basis for an integrated approach, as well as the advantages (and limitations) of this approach.

5.2 Framework for integrated approach

Currently in South Africa, the DI approach is in the process of being standardised and has been accepted for wide-scale implementation by the South African National Roads Agency Limited (SANRAL). The Swiss approach is expected for inclusion into the Swiss standards for 2013, however, only basic guidelines for the approach have been presented in Swiss standard SIA 262/1 to date. The aim of this study was to improve the accepted DI approach, by supplementary use of the Torrent method (in accordance with Swiss standard SIA 262/1).

Based on the findings presented in Chapter 4, it is proposed that the integrated approach be used to provide a tentative/preliminary indication of the expected k_{OPI} value, based on the non destructive k_{T} value measured. This presents opportunity for a number of practical applications.

5.2.1 Full implementation: neglecting moisture influence

It has been identified that moisture has a pore blocking effect on gas permeability based test methods. In particular, the effect of moisture on the Torrent method has been discussed in great detail. In accordance with the Swiss approach, the following criteria are proposed in order to limit the effects of moisture on the air-permeability measurement (Jacobs et al., 2009; Denarie et al., 2011; Torrent et al., 2012):

- Using electrical impedance with an instrument such as the concrete encounter instrument (e.g. Tramex CME4 Elcometer), the moisture content (by % mass) should not exceed 5.5%.

- Using electrical resistivity with a Wenner probe instrument (e.g. Proceq Resipod), the upper limit electrical resistivity values of 10 and 20 kΩ.cm apply to CEM I (viz. PC without reactive mineral additions) and blended cements (e.g. PC with cement extender FA) respectively. If the temperature is not between 15°C and 25°C, an appropriate conversion of electrical resistivity is described.

The results from Chapter 4 suggest that (provided these moisture requirements are met), the effect of moisture on the Torrent method is small. However, in order to allow for the degree of uncertainty, two worst case statistical boundary lines have been developed (Section 4.5.5). These represent the approximate mean minus one standard deviation (or standard error) and the limiting range (maximum values). These have been presented in Figures 4.20 and 4.21. Worksheets for assessment of these limiting values have been drafted in Appendix E (Section 12.1).

5.2.2 Full implementation: accounting for moisture influence

The findings do suggest that (even within the Swiss recommendations) the influence of moisture has a measurable effect on the Torrent method. Two methods (Section 4.5.4) have been presented in order to account for moisture, these may be summarised as follows:

(i) Simplistic approach for moisture correction: The three sets of concrete samples (summer 35 days, summer 90 days and winter 40 days) were tested with varied mass moisture percentages. For each of these sets, a separate correlation curve was constructed. These have been presented in Figure 4.15 and 4.16. Worksheets for assessment of these limiting values have been drafted in Appendix E (Section 12.2).

(ii) Multiple linear regression for moisture correction. The multiple linear regression allows us to describe the OPI value (k_{OPI}) in terms of both Torrent measurement (k_{T5}) and mass moisture percentage (m% - using electrical impedance). This has been described by Equation 4.4.

If it is required to account for moisture when implementing the integrated approach, the method (i-ii) which results in the higher k_{OPI} value should be selected.

5.2.3 Partial implementation: a more comprehensive durability assessment

The correlation also creates an opportunity for a more comprehensive investigation of RC structures. This is termed partial implementation, as the OPI test (using core extraction) is used independently to determine whether or not performance-based requirements are met. The correlation may be used as follows:

1. To reduce the number of cores to be extracted: One of the known reservations by owners of structures is the need for core extraction. The correlation presents an opportunity for fewer cores to be extracted by calibration with Torrent and OPI readings at the same location. Measurements using both methods should confirm the correlation presented in this study.

2. To enlarge the testing areas and total surfaces covered: By a similar calibration to that mentioned above, the correlation presents an opportunity to test surfaces which may not be able to be tested using partially destructive methods. These may include structural columns, shear walls and thin concrete floor slabs.
3. For weak point detection of critical structural elements: This may provide valuable knowledge for provision of maintenance or rehabilitation.
4. For investigation into the relationship between cores, the 'real' test surface and mock up panel: The correlation also presents possibilities for investigation into the differences between mock-up panel and the 'real' structures concrete quality.

This framework highlights the advantages of incorporating the Torrent method into the SA DI approach. The Torrent method should be carried out in strict accordance with the current recommendations proposed for the Swiss approach. If the requirements are not met by either of the methods presented in Sections 5.2.1-5.2.2, core extraction and full adoption of the DI approach is recommended.

Use of the integrated approach framework presents the opportunity for verification and updating of the correlation. By performing testing on multiple real structures, the effect of testing environment (in particular moisture), material selection, and various other influencing factors may be further explored.

5.3 Summary

The results and conclusions presented in Chapter 4 created the possibility for a number of practical applications. These included full implementation strategies by (1) means of a worst case statistical range, as well as (2) by accounting for moisture. A partial implementation was also presented in order to achieve a more comprehensive durability study of a structure.

CHAPTER 6

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview

The focus of this study was to investigate the potential for an integrated performance-based approach, using the OPI test and Torrent method. In particular, the aim was to provide a practical means for improving the approach adopted in South Africa by supplementary use of the Torrent method. The results have shown that both gas-permeability based approaches are sensitive to common concrete factors (or parameters) which affect durability. The experimental correlation developed was examined critically, with particular interest paid to the uncertainty due to the moisture content of concrete at testing. A few options for practical implementation of these results have been presented, along with a general discussion of the integrated approach framework.

6.2 Conclusions

6.2.1 Effect of test variables on OPI test and Torrent method

The OPI test and Torrent method were found to be highly sensitive to intrinsic (cement type, w/c ratio) and extrinsic (environmental exposure) factors. The following key trends were identified:

- Both OPI test and Torrent method showed clear distinction between 100% PC and 50/50% PC/GGBS concretes. In particular, the addition of cement extender GGBS resulted in an appreciable increase in gas-permeability. This was more severe for summer environmental exposure conditions, due to the dependence of GGBS (a latent hydraulic binder) on available moisture for curing.
- For w/c ratios 0.50, 0.65 and 0.80, the OPI test and Torrent method showed clear distinction. The w/c ratio was identified as one of the main controlling parameters for gas-permeability.
- The results suggest that the method used to achieve poor compaction was not successful, resulting in varied results with no clear trend. It was identified that the combined effect on compaction and curing may require further investigation.
- Winter samples were tested at 35 - 40 days, showing a considerable reduction of gas-permeability for both 100% PC and 50/50% PC/GGBS concretes. The

50/50% PC/GGBS concretes were greatly affected by the lack of moisture available for hydration in the summer condition (in comparison with the 100% PC concretes).

- Testing age appeared to have an appreciable effect on the blended cement by the OPI test only. The Torrent method showed a similar trend, however, it was not conclusive. This was due to the uncertainty surrounding moist concretes at the time of testing.

It was concluded that the permeability of concretes tested using the OPI test may (to a large extent) eliminate the effect of moisture as a result of the preconditioning required. However, the Torrent method measurement gives an indication of the combined effect of environmental exposure condition (curing) and moisture content at the time of testing. This moisture effect was carefully considered in the correlation of the OPI test and Torrent method which followed.

6.2.2 Correlation between OPI test and Torrent method measurements

Previous studies show that the correlation between k_{OPI} and k_{Ti} measurements should be expected. Results from this study showed a good fit ($R^2 = 0.948$) when fitted with a power function. The function is described by Equation 4.1, and illustrated in Figure 4.10.

$$k_{Ti} = 0.0341\, k_{OPI}^{\ 3.0296} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

where: k_{Ti} = k-value from the Torrent method (x 10^{-10} m/s)

k_{OPI} = k-value from the OPI test (x 10^{-16} m^2)

Previous research confirmed the choice of best fit function, and generally represented a similar trend. There was, however, found to be a notable difference between k_{OPI} versus k_{Ti} correlations from previous studies. Data from three independent sets of testing performed in this study, resulted in very similar trends. An explanation for the discrepancies between studies has been presented in Section 4.6.

6.2.3 Practical implementation of the integrated approach

Three methods have been presented in Chapter 5, which allow the engineer to select the type of implementation of the integrated approach. These may be summarised as follows:

1. Full implementation: neglecting moisture influence

In this approach, the requirements on moisture content are satisfied if within the current Swiss approach recommendations. It is shown that the effect of moisture within these limits is unlikely to affect the outcome of a durability assessment. However, the correlation provides three indicative lines, which show approximations for statistical standard deviation and the absolute range. Uncertainty with regards to moisture content may be investigated by observation of these limiting curves.

2. **Full implementation: accounting for moisture influence**

In this approach the requirements on moisture content are again satisfied if within the current Swiss approach recommendations. Two alternative approaches are presented, which allow the engineer to make an informed decision regarding OPI prediction by accounting for the known influence of moisture on gas-permeability. Two methods are presented:

- Simplistic approach
- Multiple linear regression

3. **Partial implementation: a more comprehensive durability assessment**

The supplementary use of the Torrent method is proposed in order to achieve a more comprehensive investigation of RC structures. However, the performance-based specifications should be achieved by the DI approach (or k_{OPI}).

6.2.4 Moisture measurement in accordance with the Swiss approach

Extensive experimental work performed in the study supports the use of electrical resistivity and electrical impedance for assessing the limiting moisture content in concrete. Of particular interest were the similarities between effect of cement type (50/50% PC/GGBS) on electrical resistivity and mass moisture. The Swiss approach has accommodated for this influence for electrical resistivity only. This appears justified, as the effect of cement extender on electrical resistivity is more pronounced. A number of recommendations are made for further investigation into the effects of moisture on the Torrent method.

6.3 Recommendations

Based on the work presented in this study, the following recommendations are made:

6.3.1 The Durability Index approach

Further research is recommended in the following areas:

- The samples prepared in this study were of particularly high permeability. Problems were encountered with regards to chipping of samples during preparation. This defect has been identified in the DI approach guidelines (Alexander et al., 2010), however, quantification of these defects would be desirable in order to determine whether or not a sample is suitable for testing.
- The OPI test uses a linear regression coefficient of pressure versus time to determine whether or not the test result is valid. Due to the particularly high permeability of many of these samples, in some cases the correlation coefficient (R^2) was not acceptable, however, a high degree of consistency between other

valid samples was achieved. Further research is proposed, to investigate the validity of using R^2 for high permeability concretes to conclude on test validity.

6.3.2 The Swiss approach

Further research is recommended in the following areas:

- The current Swiss approach guidelines state (in the absence of testing instruments): *"The achievement of the above conditions depends strongly on the ambient conditions and will generally be reached when:(a) the curing ended 3–4 weeks prior to the test, (b) more than 2–5 days have passed after the last ingress of water in the concrete by, for instance, rain, spray, or thaw"*. However, based on observations made on drying concretes (in a controlled laboratory) for the winter environmental exposure (Appendix D), it is expected that fewer than 5 days since previous wetting may be inadequate for ensuring the concrete is sufficiently dry.
- The effect of various cements and cement extenders on both electrical resistivity and mass moisture (using electrical impedance) requires further investigation.

6.3.3 The Integrated approach

Further research is recommended in the following areas:

- Testing on real structures would allow verification and refinement of the correlation developed. In particular, through partial implementation of the approach, the correlation may be adjusted for a particular RC structure. A greater database for permeability measurement may create potential for a fully probabilistic integrated approach in the future.
- Further laboratory-based experimental work, with the use of various materials such as cement extenders and coarse aggregates, is recommended.

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APPENDICES

8 APPENDIX A: SANRAL SPECIFICATIONS

8.1 Table 6000/1: Concrete durability specification targets

* Note to compiler: Insert Table 6000/1: Concrete durability specification targets (Civil engineering structures only) as of 12 August 2009.

Table 6000/1 : Concrete Durability Specification Targets (Civil Engineering Structures only)

Last Update: [illegible]

Carbonation-Induced Corrosion (from Atmospheric & Industrial)

Designation	Description	Condition of Exposure	Description of Exposure	Typical Examples where applicable	Recommended Minimum Cover (mm)	Design Durability Index Parameters/Cover Depths within Exposure Condition – [illegible]				
							OPI (log scale)		Sorptivity (mm/√h)	
						Cover Depth (mm)	Recommended value	Minimum value	Recommended value	Maximum value
XC1	[illegible]	Mild	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
XC2	Permanently wet, rarely dry		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
XC3	Moderately dry	Moderate	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
XC4	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Cyclic wet and dry	Severe	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

WARNING: [illegible]

NOTE: [illegible]

Chloride-Induced Corrosion (from Groundwater, Seawater & Sea spray)

Designation	Description	Condition of Exposure	Description of Exposure	Typical Examples where applicable	Recommended Minimum Cover (mm)	Design Durability Index Parameters/Cover Depths within Exposure Condition – [illegible] Year Life						
							Chloride Conductivity (mS/cm)				Sorptivity (mm/√h)	
							Typical Binder Blends					
						Cover Depth (mm)	[illegible]	[illegible]	[illegible]	[illegible]	Recommended value	Maximum value
[illegible]	[illegible]	Very severe	[illegible]	[illegible]	[illegible]	40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Severe	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Extreme	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Tidal, splash & spray zones	Extreme	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Notes

1. Exposure Classes

[illegible]

[illegible]

[illegible]

2. Cover

[illegible]

[illegible]

[illegible]

[illegible]

3. OPI

[illegible]

[illegible]

[illegible]

[illegible]

4. Chloride Conductivity

[illegible]

[illegible]

5. Sorptivity

[illegible]

[illegible]

8.2 SANRAL performance-based specification extracts

8.2.1 Section B 6404: Concrete quality

(ii) Durability Parameters

Water sorptivity: Sorptivity is sensitive to surface effects and may be used to assess the effectiveness of initial curing.

Oxygen permeability: Permeability is sensitive to changes in the coarse pore fraction and thus a means of assessing compaction of concrete. It is used to quantify the microstructure of the concrete and sensitive to macro-defects such as voids and cracking.

Chloride conductivity: Chloride conductivity provides a method of characterisation of concretes in the marine environment and is used to assess the chloride resistance of concrete.

Cover concrete: Cover concrete is the outer concrete layer that protects reinforcing steel. Concrete cover is a requirement for all concrete whether specified as durability concrete (Class „W") or normal reinforced concrete.

Individual Cover Depth Measurement (CDM): Individual cover depth measurement determined by an electromagnetic cover meter, complying with BS 1881, Part 204.

Average Cover: The average of at least 30 individual CDM"s per m^2 determined on a clearly identified area.

The mean average cover determined for the scanned area per structure

(iv) Environmental Classes of Exposure

For this project, the environmental classes for carbonation and chloride exposure for the different structural elements are as shown below in Table B6404/3.

Table B6404/3: Environmental classes of exposure for elements of structure

Element	Carbonation Environment (PE)	Chloride Environment (CC)
Foundations	N/A	XS1
Substructures	XC3	XS1
Superstructures	XC3	XS1

Table B6404/4: Durability parameters acceptance ranges

Acceptance criteria	Test No/Description/Unit				
	B8106 (g)(i) Water Sorptivity (mm/h)	B8106 (g)(ii) Oxygen Permeability (log scale)			
		Parapets	Sub structures	Super structures	Etc. for other members
Concrete made, cured and tested in the laboratory using trial panels	< 10.0	< a[8]	< c[8]	< e[8]	< g[8]
Full acceptance of in situ using Test panels	< 10.0[1]	< a[8]	< c[8]	< e[8]	< g[8]
Conditional acceptance of in-situ concrete based on results of test panels	Not applicable[1]	b[8] - a[8]	d[8] - c[8]	f[8] - e[8]	h[8] - g[8]
Rejection based on results of test panels	Not applicable[1]	< b[8]	< d[8]	< f[8]	< h[8]

Note to compiler: The limiting values for OPI to be inserted in Table B6404/4 i.e. values a, c, e and g shall be the "Recommended" values and values b, d, f and h shall be the "Minimum" values obtained from the Table 6000/1, discussed above. The values to be used are based on the cover requirements and therefore vary for the different cover ranges as well as environmental categories chosen.

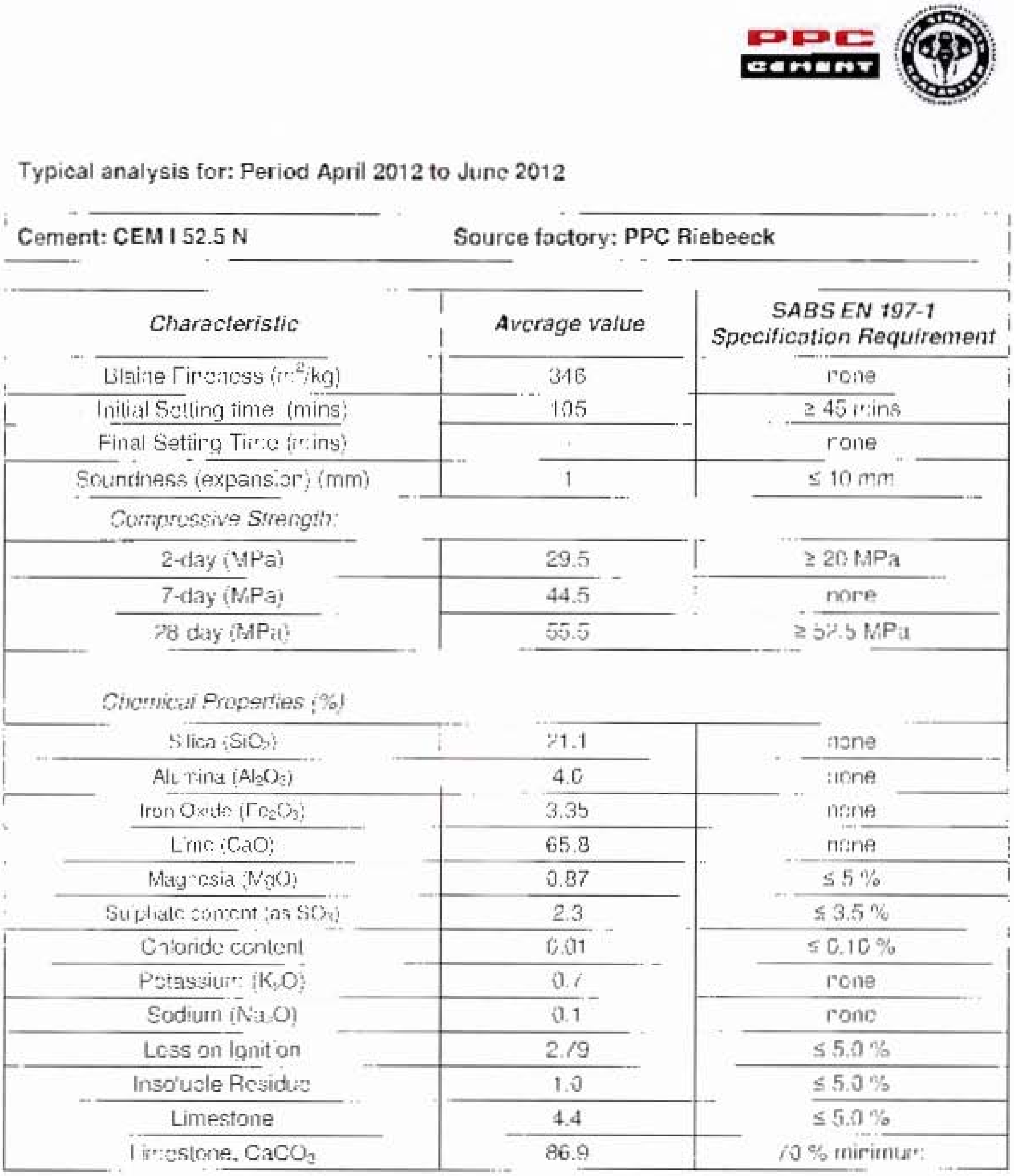
8.2.2 Section B 8100: Testing materials and workmanship

Table B8212/1: Table of reduced payments for oxygen permeability index – 'W' class concrete

DESCRIPTION OF TEST	OXYGEN PERMEABILITY INDEX (LOG SCALE)	PERCENTAGE (%) PAYMENT
Full acceptance	See Table B6404/4 for limit	100 %
Conditional acceptance (with reduced payment)	See Table B6404/4 for limit	80 %
Rejection	See Table B6404/4 for limit	Not Applicable

9 APPENDIX B: MIX SPECIFICATION DETAILS

9.1 PPC CEM I 52.5 N Portland cement composition



Typical analysis for: Period April 2012 to June 2012

Cement: CEM I 52.5 N **Source factory: PPC Riebeeck**

Characteristic	*Average value*	*SABS EN 197-1 Specification Requirement*
Blaine Fineness (m^2/kg)	346	none
Initial Setting time (mins)	105	≥ 45 mins
Final Setting Time (mins)		none
Soundness (expansion) (mm)	1	≤ 10 mm
Compressive Strength:		
2-day (MPa)	29.5	≥ 20 MPa
7-day (MPa)	44.5	none
28 day (MPa)	55.5	≥ 52.5 MPa
Chemical Properties (%)		
Silica (SiO_2)	21.1	none
Alumina (Al_2O_3)	4.0	none
Iron Oxide (Fe_2O_3)	3.35	none
Lime (CaO)	65.8	none
Magnesia (MgO)	0.87	≤ 5 %
Sulphate content (as SO_3)	2.3	≤ 3.5 %
Chloride content	0.01	≤ 0.10 %
Potassium (K_2O)	0.7	none
Sodium (Na_2O)	0.1	none
Loss on Ignition	2.79	≤ 5.0 %
Insoluble Residue	1.0	≤ 5.0 %
Limestone	4.4	≤ 5.0 %
Limestone, $CaCO_3$	86.9	70 % minimum

Cement: CEM I 52.5 N **Source factory: PPC Riebeeck**

Characteristic	*Average value*	*SABS EN 197-1 Specification Requirement*
90 micron - retained/ passing (please indicate)	4%	retained
45 micron - retained/ passing (please indicate)	20%	retained
32 micron - retained/ passing (please indicate)	32.4%	retained
25 micron - retained/ passing (please indicate)	39.5%	retained

Bogue analysis for Clinker produced for the corresponding period

Free CaO	1.33
C3S	61.61
C2S	17.22
C3A	6.77
C4AF	10.63

Comments:

Results of Tests are conducted according to the methods specified by SANS 50197-1/ SABS EN 197-1:2000.

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November 2012

9.2 AfriSam Slagment (Ground Granulated Blast Furnace Slag) composition

4. Sample Results

4.1 Table 1 Chemical Analysis 2012

Test %	SANS 55167-1 & SANS 1491-1 Requirements	January	February	March	April	May	June	July	August	September	October	November	December
LOI	≤ 3.0	-0.32	-0.18	0.90	0.50	0.40	0.38	0.31					
SiO_2	x	40.20	26.82	33.74	38.54	37.01	37.98	39.45					
Al_2O_3	x	15.18	14.74	13.79	13.36	12.76	13.16	12.84					
Fe	x	0.20	1.00	0.58	0.45	0.82	0.46	0.36					
CaO	x	34.40	35.24	36.93	39.34	37.10	37.40	38.80					
MgO	≤ 18	6.73	7.30	8.22	7.113	6.06	7.69	7.34					
K_2O	x	1.05	1.03	0.98	1.011	0.94	0.95	0.92					
TiO_2	x	0.78	0.77	0.91	0.60	0.83	0.83	0.58					
MnO	x	0.91	1.26	1.05	0.87	0.74	0.80	0.47					
SO_3	≤ 2.5	0.56	0.77	0.84	0.39	0.30	0.58	0.48					
Free H_2O	< 1.0	0.33	0.42	0.53	0.51	0.52	0.43	0.28					
Sulide	≤ 2.0	0.98	1.1	1.10	0.70	0.96	0.88	1.09					

9.3 19 mm Greywacke aggregate grading curve

SIEVE ANALYSIS

Uct Concrete Laboratory

Aggregate sample:

19mm Graywacke

2500g

Test No: 4

Date: 06/2010

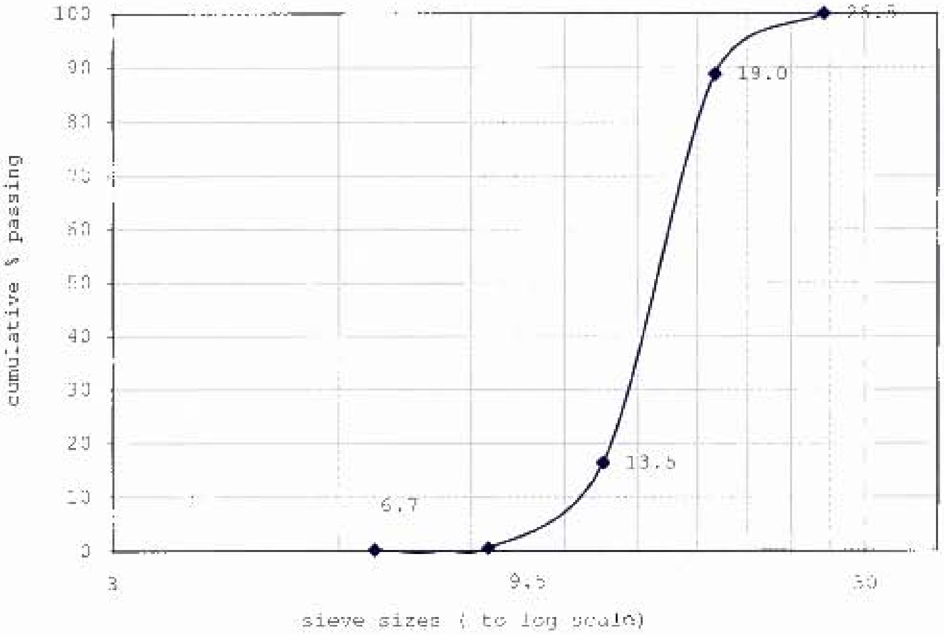
Tested by: CMAY / Lungelo

Finess Modulus: 2.9

Loose Bulk Density (kg/m^3) 1440

Compacted Bulk Density (kg/m^3) 1570

Sieve opening (mm)	MASS Sieve (g)	MASS Sieve + aggr. (g)	MASS retained (g)	Mass retained %	cum. Retained (%)	cum. % passing (%)
26.5	0	0	0	0	0	100
19.0	1510	1790	280	11.2	11.2	88.8
13.5	1355	3165	1810	72.4	83.6	16.4
9.5	1420	1815	395	15.8	99.4	0.6
6.7	1475	1485	10	0.4	99.8	0.2
PAN	1185	1190	5	0.2		
		sum mass	2500			



9.4 Klipheuwel sand grading curve

SIEVE ANALYSIS

Uct Concrete Laboratory

Aggregate sample: KLIPHEUWEL SAND

600g

Test No:

Date: 06/2010

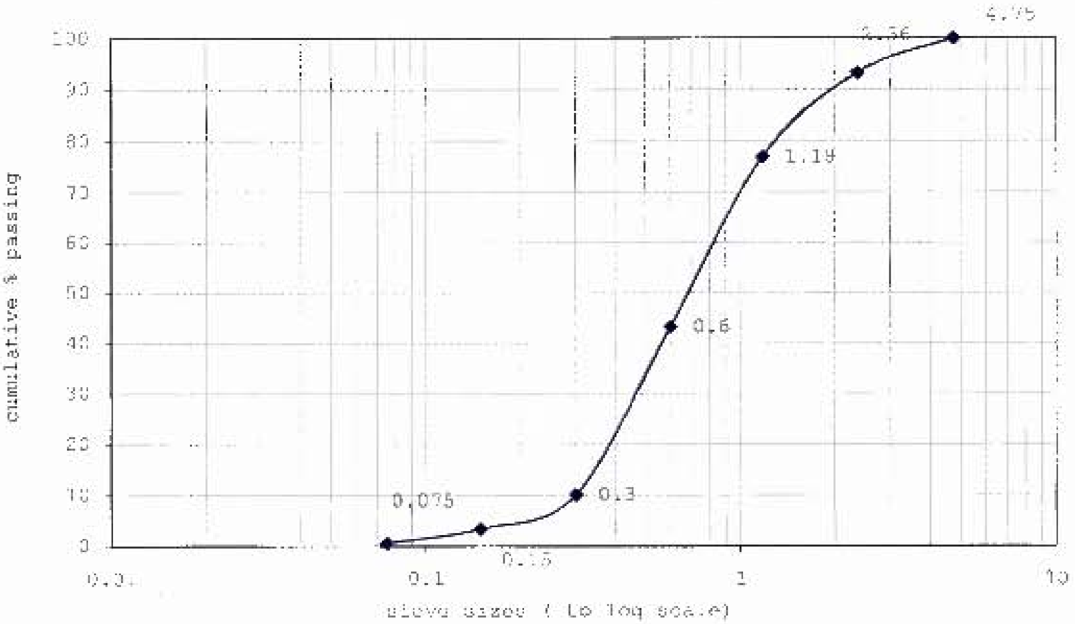
Tested by: C. May

Finess Modulus: 2.7

Loose Bulk Density (kg/m^3) 1439

Compacted Bulk Density (kg/m^3) 1590

Sieve opening (mm)	MASS Sieve (g)	MASS Sieve + aggr. (g)	MASS retained (g)	Mass retained %	cum. Retained (%)	cum. % passing (%)
4.75	465	465	0	0	0	100
2.36	415	475	60	6.7	6.7	93.3
1.18	350	495	145	16.3	23.0	77.0
0.6	505	805	300	33.7	56.7	43.3
0.3	280	575	295	33.1	89.9	10.1
0.15	520	580	60	6.7	96.6	3.4
0.075	260	285	25	2.8	99.4	0.6
PAN	495	500	5	0.6		
		sum mass	890			

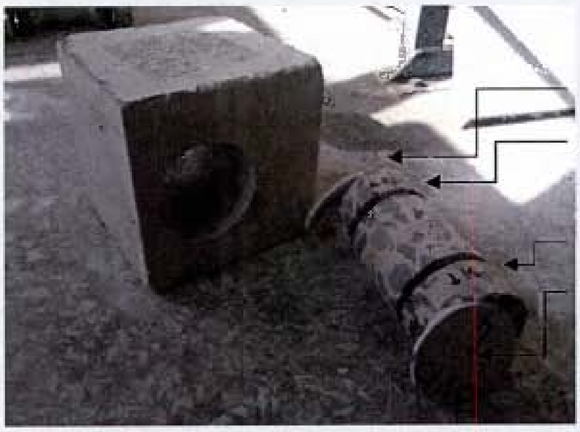


10 APPENDIX C: TESTING DETAILS

10.1 Experimental work photographs

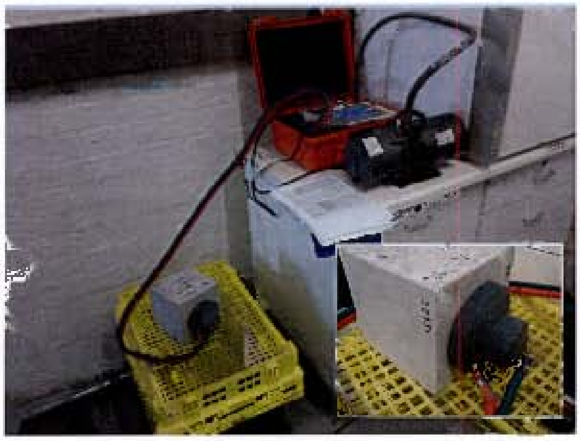
10.1.1 Oxygen permeability index test

Oxygen permeability index test (in accordance with the DI approach)

Image	*Description*
	*5mm edge removed* *OPI specimen 1* *OPI specimen 2* *5mm edge removed* *Extraction of cores from 150 mm cubes and cutting of OPI test specimens (30 ± 2mm thickness)*
	*OPI test in progress, databank recorder for each test chamber*

10.1.2 Torrent method

Torrent method (in accordance with the Swiss approach)	
Image	*Description*
	*Moisture measurement* *[Elcometer CME4 moisture meter, Tramex]*
	*Moisture measurement by electrical resistivity (side view)* *[Resipod, Proceq]*
	*PermeaTORR instrument calibration*



PermeaTORR instrument test in progress

10.2 Supplementary non-destructive test methods for moisture conditioning

10.2.1 Four-point probe method

The four-point probe (also commonly known as the *Wenner probe*) is used to measure the electrical resistivity of concrete. This measurement represents a concretes resistance to ionic movement in the pore water. Resistivity provides an indication of the expected rate of ingress by harmful chemicals (e.g. carbon dioxide, chlorides and sulphates) and hence insight into the concretes durability (Ballim et al., 2009). An alternating electrical current is sent between the two outer probes, and the potential difference across the inner probes measured by a voltmeter. In the past, electrical resistivity has been used to investigate moisture condition, concrete quality, and corrosion risk (Romer, 2005; van Grieken, 2008). Figure 10.1 shows the four-point (Wenner) probe method test schematic.

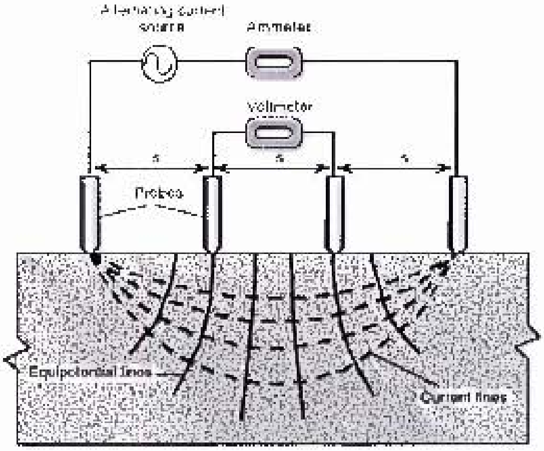


Figure 10.1: Four-point 'Wenner' probe method test schematic (Malhotra et al., 2004)

The probes were positioned diagonally across the cube surface (Section 10.1.2). This was necessary since the cube edge size (150mm) was the same as the outer-to-outer probe spacing. For purposes of this study, the effect of sample size on resistivity (Morris et al., 1996) was assumed negligible.

10.2.2 Mass moisture

An alternative to the use of electrical resistivity for moisture content measurement is the use of electrical impedance. The electrical impedance measurement provides an indication of the resistance to parallel low frequency signals in the concrete surface (approximately 12.5 mm) (Tramex Ltd., 2010). The instrument used for this study was the 'Tramex Encounter Meter CME4', which provides an indication of the mass moisture between 0 and 6% (mass water/mass concrete in %). This instrument has been recommended in the most recent Swiss approach guidelines for moisture assessment (Torrent et al., 2012).

11 APPENDIX D: EXPERIMENTAL RESULTS

11.1 Outlier removal for OPI test and Torrent method data

Due to the unique nature of the experimental programme, outliers were removed in two stages:

1. The first stage for outlier detection was based on that presented by ASTM E 178 - 90 (Reapproved 1989).
2. Thereafter, engineering judgement was applied to remove data which appeared contradictory to the general trend. These values were determined using w/c ratio as the controlling parameter. It was only necessary in a few cases, as the ASTM method appeared quite effective at removing irregular data.
3. It should be noted that for k_{OPI} the arithmetic mean (Arimean) was used in accordance with the current DI approach guidelines, while for k_{Ti} the geometric mean (Geomean) was used, as specified in the Swiss approach.

An extract from the outlier detection in accordance with ASTM E 178 - 90 for OPI test data is shown below:

Number of observations	n	8	12
Upper significance level chosen		0.05	0.05
True level of significance		0.1	0.1
Critical value for T	T	2.032	2.285

(Taken 2 identical cubes as on samples - i.e. 6 readings)

(Double sided test)

35 DAY STATISTICAL ANALYSIS								
Sample ID	k_{OPI}	k_{OPI} (10^{-10} m/s)	k_{OPI} ARImean (10^{-10} m/s)	Standard deviation k_{OPI} (10^{-10} m/s)	|| T ||	Outlier test	Corrected mean k_{OPI} value (10^{-10} m/s)	Corrected mean k_{OPI} value (10^{-10} m/s)
28	6.16E-10	6.16	7.23	2.23	0.48	Not outlier	7.17	6.99
	7.27E-10	7.27			0.01	Not outlier		
	3.88E-10	3.88			1.50	Not outlier		
	1.06E-09	10.64			1.53	Not outlier		
	7.34E-10	7.34			0.05	Not outlier		7.40
	8.11E-10	8.11			0.39	Not outlier		
	6.76E-10	6.76			0.21	Not outlier		
	2.56E-10	2.56			2.10	Outlier		

11.2 Overview of test results

A summary of the complete set of test results is provided in the tables below. Careful attention should be paid to the small sample sizes from which the standard deviations (presented below) are calculated.

The cells shown in red were removed as outliers, and hence have been omitted in the tables which follow.

Test results - 35 day summer environment

		kOPI ARI mean (m/s)	kOP Std dev (m/s)	kT Geomean (m2)	kT Std dev (m2)	Mass moisture mean (%)	Mass moisture Std dev (%)	Electrical resistivity mean (kohm.cm)	Electrical resistivity Std dev (kohm.cm)	Strength mean (MPa)	Strength Std dev (MPa)
No readings		4	4	3	3	3	3	3	3	4	4
w/b ratio	Sample ID										
0.5	101	4.98E-10	1.95E-10	4.21E-16	3.46E-16	4.67	0.12	25.47	0.79	37.97	1.30
	102	2.49E-10	5.58E-11	1.15E-16	5.09E-17	4.93	0.23	24.00	1.51		
	1B1	2.75E-10	1.77E-10	4.67E-17	8.19E-17	5.00	0.42	24.30	3.14	37.67	1.97
	1B2	2.58E-10	3.40E-11	4.32E-17	1.65E-17	4.60	0.58	24.30	1.15		
	201	4.97E-10	1.90E-10	7.85E-16	4.05E-16	4.20	0.20	208.50	43.55	30.33	1.45
	202	4.73E-10	2.47E-10	2.04E-16	2.82E-16	4.60	0.53	155.20	47.35		
	2B1	5.39E-10	2.82E-10	3.00E-15	1.18E-16	4.27	0.23	210.93	42.99	28.40	1.11
	2B2	5.04E-10	2.48E-10	7.77E-16	2.63E-16	4.27	0.31	175.13	26.19		
0.65	301	3.50E-10	1.76E-10	8.05E-17	3.87E-17	4.80	0.40	30.60	4.62	28.47	0.64
	302	3.54E-10	1.06E-10	5.08E-16	1.59E-16	5.20	0.35	24.00	2.05		
	3B1	3.56E-10	8.93E-11	2.13E-16	1.59E-16	4.67	0.64	29.43	2.85	53.53	0.81
	3B2	4.14E-10	2.80E-10	1.17E-16	5.42E-16	4.80	0.65	22.63	3.88		
	401	8.87E-10	2.54E-10	2.49E-15	1.05E-15	4.20	0.20	145.60	72.46	22.03	0.45
	402	9.90E-10	4.48E-10	1.23E-15	3.73E-15	4.20	0.23	164.40	65.49		
	4B1									23.63	0.57
	4B2	1.14E-09	5.53E-10	2.57E-15	2.00E-15	4.33	0.76	186.80	85.40		
0.8	501	7.03E-10	2.75E-10	1.04E-15	5.56E-16	4.80	0.69	25.83	6.48	23.20	0.33
	502	7.25E-10	2.95E-10	4.76E-15	1.66E-14	4.13	0.46	28.40	7.45		
	5B1	7.84E-10	4.05E-10	2.71E-16	4.22E-16	4.80	0.53	25.77	5.25	23.00	0.72
	5B2										
	601	1.18E-09	1.92E-10	7.16E-15	4.53E-15	5.00	0.54	214.67	119.09	15.47	2.00
	602	8.94E-10	1.57E-10	4.29E-15	1.29E-15	4.47	0.70	105.37	26.98		
	6B1	1.17E-09	2.36E-10	5.03E-15	7.65E-15	4.47	0.50	157.43	40.21	17.20	1.93
	6B2	9.33E-10	2.29E-10	1.41E-15	1.12E-15	4.47	0.46	86.43	19.69		

Test results - 90 day summer environment											
		kOPI AB mean (m/s)	kOPI Std dev (m/s)	kT Geomean (m2)	kT Std dev (m2)	Mass moisture mean (%)	Mass moisture Std dev (%)	Electrical resistivity mean (kohm.cm)	Electrical resistivity Std dev (kohm.cm)	Strength mean (MPa)	Strength Std dev (MPa)
No readings		4	4	3	3	3	3	3	3	4	4
w/b ratio	Sample ID										
0.5	1J3	5.36E-10	3.28E-10	2.31E-15	1.55E-16	3.47	0.12	36.63	2.78	39.50	2.17
	1J4	4.48E-10	4.94E-11	2.87E-15	1.12E-16	3.60	0.72	32.97	0.31		
	1J5	4.29E-10	1.63E-10	2.77E-16	1.68E-16	5.19	0.12	30.00	2.72		
	1B3	2.21E-10	1.34E-10	5.63E-17	6.51E-17	3.20	2.46	31.33	2.25	40.75	0.46
	1B4	2.12E-10	1.25E-10	5.28E-17	7.42E-17	4.85	0.35	28.90	0.65		
	2J3	4.54E-10	3.99E-11	6.24E-15	1.11E-16	3.60	0.00	351.33	21.14	31.45	0.72
	2J4	3.63E-10	4.30E-11	4.95E-15	8.88E-16	3.67	0.25	235.33	22.50		
	2J5	3.30E-10	1.97E-10	2.75E-15	1.45E-14	3.60	0.01	226.50	3.45		
	2B3	3.53E-10	7.91E-11	5.38E-15	1.19E-16	4.00	0.20	280.00	40.24	32.80	1.06
	2B4	3.94E-10	6.06E-11	6.95E-15	4.30E-15	[illegible]	0.12	225.00	7.00		
0.65	3J3	4.57E-10	1.02E-10	6.72E-15	1.59E-15	3.94	0.31	59.70	19.48	32.40	2.29
	3J4	3.73E-10	9.69E-11	3.60E-16	[illegible]	4.47	0.23	34.33	6.90		
	3J5	4.37E-10	1.20E-10	4.52E-16	2.35E-16	3.87	0.23	49.20	20.70		
	3B3	3.84E-10	2.63E-10	7.41E-17	1.39E-16	4.47	0.31	42.87	5.46	38.40	1.14
	3B4	5.73E-10	3.86E-10	2.80E-16	1.73E-17	4.87	0.12	32.93	6.50		
	3B5	2.35E-10	3.44E-11	7.06E-17	2.58E-17	4.73	0.23	35.90	5.88		
	4J3	7.12E-10	9.41E-11	2.12E-15	1.89E-15	3.60	0.30	412.67	136.02	25.75	1.27
	4J4	7.50E-10	1.66E-10	[illegible]	[illegible]	4.13	0.12	187.47	11.40		
	4J5	5.45E-10	1.40E-10	2.26E-15	2.92E-15	4.00	0.20	279.67	[illegible]		
	4B3	6.36E-10	1.50E-10	1.35E-15	2.65E-16	3.79	0.12	272.33	38.47	25.15	1.56
	4B4	1.34E-09	2.27E-10	2.56E-15	8.33E-16	4.07	0.23	[illegible]	13.72		
	4B5	4.24E-10	3.77E-10	4.20E-15	1.49E-15	3.60	0.30	311.33	55.01		
0.8	5J3	4.29E-10	1.43E-10	6.62E-16	6.14E-16	5.87	0.50	48.53	10.70	25.55	0.98
	5J4	4.55E-10	1.20E-10	3.44E-16	7.31E-17	4.33	0.31	37.50	4.95		
	5J5										
	5B3	8.75E-10	9.55E-10	6.96E-16	4.51E-17	4.13	0.12	45.43	23.95	25.75	2.75
	5B4	7.75E-10	1.36E-10	2.32E-15	3.51E-16	4.00	0.00	63.47	10.43		
	5B5	6.24E-10	3.00E-11	1.75E-15	9.74E-16	4.40	0.35	43.20	1.59		
	6J3	1.08E-09	2.13E-10	3.54E-15	1.25E-15	3.47	0.31	308.33	170.90	18.07	0.50
	6J4	1.28E-09	5.20E-10	1.55E-15	6.60E-16	3.87	0.12	170.00	12.17		
	6J5	1.03E-09	3.29E-10	5.09E-15	2.39E-15	4.77	0.02	414.67	151.53		
	6B3	9.58E-10	3.67E-10	3.68E-15	9.59E-15	3.50	0.20	241.00	30.51	18.95	1.81
	6B4										
	6B5										

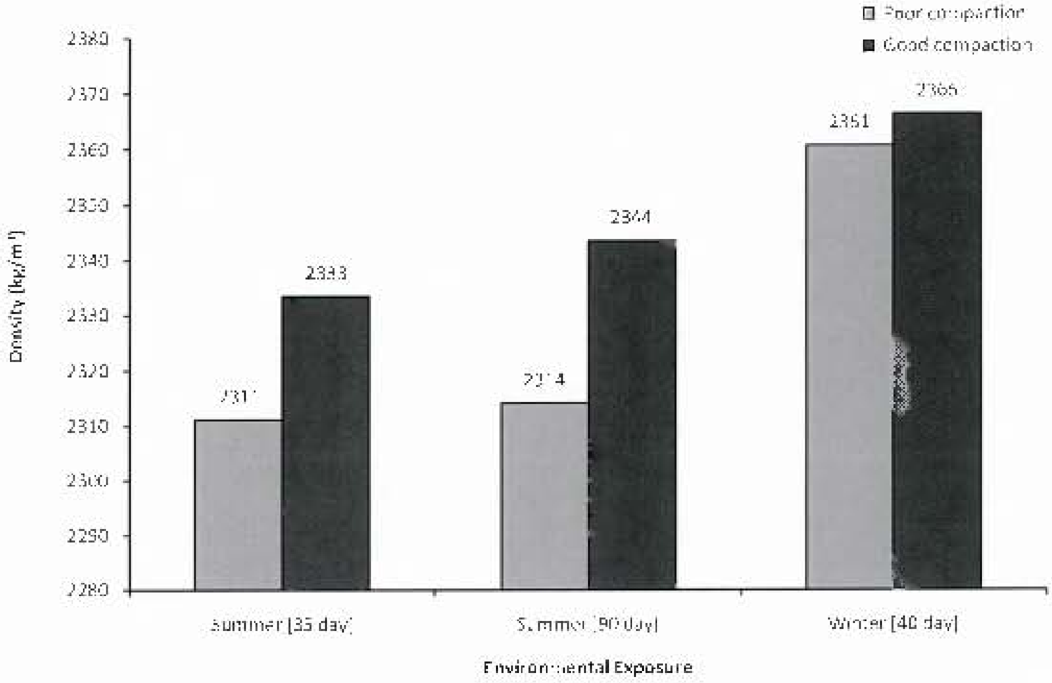
Test results - 40 day winter environment											
		kOPI Arithmean (m/s)	kOPI Std dev (m/s)	kT Geomean (m2)	kT Std dev (m2)	Mass moisture mean (%)	Mass moisture Std dev (%)	Electrical resistivity mean (kohm.cm)	Electrical resistivity Std dev (kohm.cm)	Strength mean (MPa)	Strength Std dev (MPa)
No readings		4	4	3	3	3	3	3	3	4	4
w/b ratio	Sample ID										
w/b ratio = 0.5	W1J1	6.44E-11	1.34E-11	7.27E-19	5.09E-19	5.07	0.12	14.70	0.70	31.05	1.15
	W1J2	7.42E-11	1.61E-11	2.62E-18	3.98E-18	5.20	0.20	13.57	1.43		
	W1B1	7.31E-11	3.32E-12	1.06E-18	9.45E-19	5.13	0.23	12.93	0.49		
	W1B2	7.87E-11	1.28E-11	2.55E-18	1.11E-18	5.47	0.12	14.37	1.03	33.00	1.04
	W1B3	6.81E-11	3.17E-12	1.42E-18	7.60E-19	5.53	0.12	13.53	0.59		
	W2J1	5.42E-11	8.86E-12	8.72E-19	2.68E-19	4.60	0.20	37.24	5.40	36.00	1.71
	W2J2	6.23E-11	1.95E-11	3.49E-19	2.01E-19	4.93	0.12	34.67	1.94		
	W2B1	6.94E-11	1.78E-11	6.76E-19	3.90E-19	5.13	0.42	43.20	3.82	37.13	2.53
	W2B2	4.91E-11	1.33E-11	4.36E-19	1.22E-19	5.20	0.20	38.70	1.73		
	W2B3	5.83E-11	1.70E-11	3.65E-19	7.09E-20	5.00	[illegible]	32.90	1.59		
w/b ratio = 0.65	W3J1	1.16E-10	1.49E-11	5.13E-18	2.76E-18	5.20	0.20	11.93	1.10	38.20	0.88
	W3J2	8.75E-11	1.38E-11	4.74E-18	2.81E-18	5.50	0.35	12.53	0.72		
	W3B1	9.95E-11	6.00E-12	5.92E-18	3.23E-18	5.40	0.40	13.50	1.56	36.09	1.42
	W3B2	9.63E-11	4.94E-12	2.25E-18	3.79E-19	5.53	0.12	11.33	0.55		
	W3B3	1.16E-10	1.25E-11	4.82E-18	2.18E-18	5.33	0.12	12.70	1.90		
	W4J1	1.50E-10	3.76E-11	1.66E-17	1.74E-17	5.20	0.35	31.57	0.76	25.67	1.63
	W4J2	9.97E-11	4.57E-11	3.88E-18	2.27E-18	4.67	0.31	31.80	2.86		
	W4B1	1.15E-10	9.68E-12	5.78E-18	5.20E-19	4.87	0.31	26.20	3.12	24.60	0.72
	W4B2	1.52E-10	4.99E-11	1.80E-18	6.43E-19	5.07	0.46	25.03	3.57		
	W4B3	1.77E-10	4.72E-11	5.59E-18	1.52E-18	5.20	0.20	28.00	4.31		
w/b ratio = 0.8	W5J1	1.89E-10	1.92E-11	2.19E-17	2.35E-18	5.60	0.00	13.33	0.64	29.80	0.35
	W5J2	1.43E-10	1.22E-11	7.35E-18	1.69E-18	5.33	0.23	13.33	2.71		
	W5B1	1.87E-10	4.36E-11	1.45E-17	1.01E-17	5.53	0.12	12.80	1.55	30.13	0.23
	W5B2	1.79E-10	1.54E-11	1.27E-17	5.16E-18	5.67	0.23	10.63	0.50		
	W5B3	1.64E-10	2.74E-11	1.78E-17	7.23E-18	5.53	0.31	12.32	1.45		
	W6J1	3.91E-10	7.72E-11	3.14E-17	3.55E-17	5.07	0.42	26.27	1.32	19.47	0.83
	W6J2	2.38E-10	7.85E-11	5.03E-17	3.40E-17	5.07	0.23	29.70	0.66		
	W6B1	1.88E-10	2.78E-11	2.80E-17	8.89E-18	4.53	0.12	31.70	3.04	21.87	0.64
	W6B2	1.50E-10	3.08E-11	5.38E-18	2.75E-18	5.07	0.31	27.20	2.33		
	W6B3	1.78E-10	3.75E-11	1.04E-17	5.77E-18	5.07	0.46	27.50	2.42		

11.3 Influence of compaction on concrete density and strength

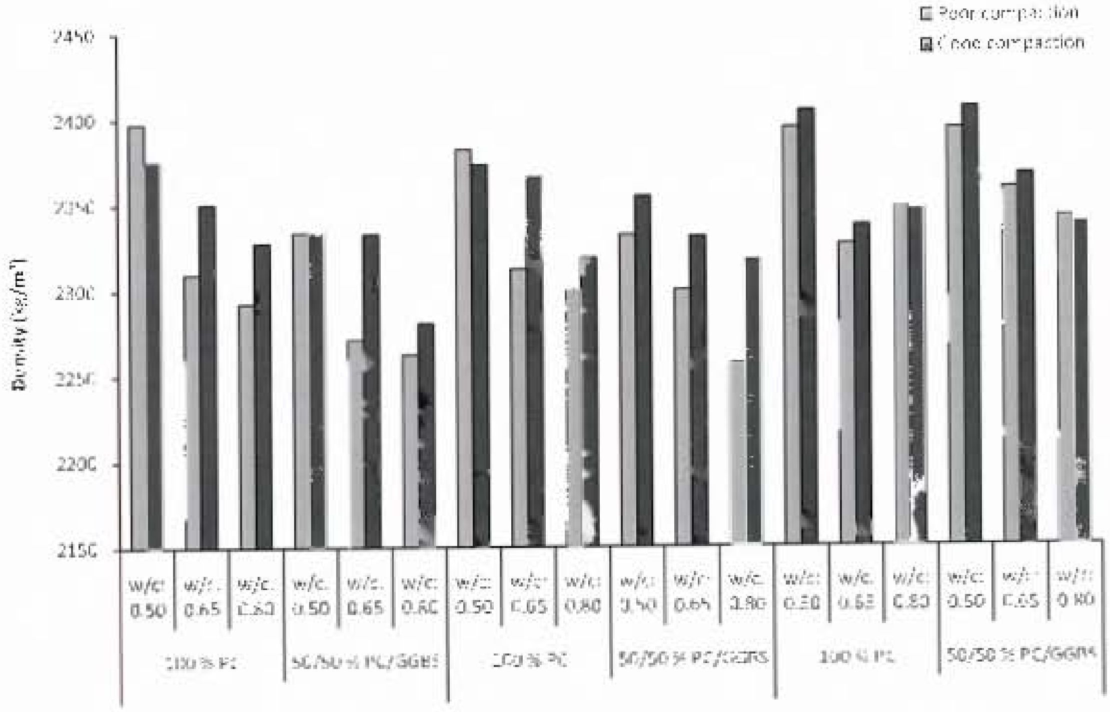
Summary of density (kg/m^3) and strength results for each environmental exposure condition:

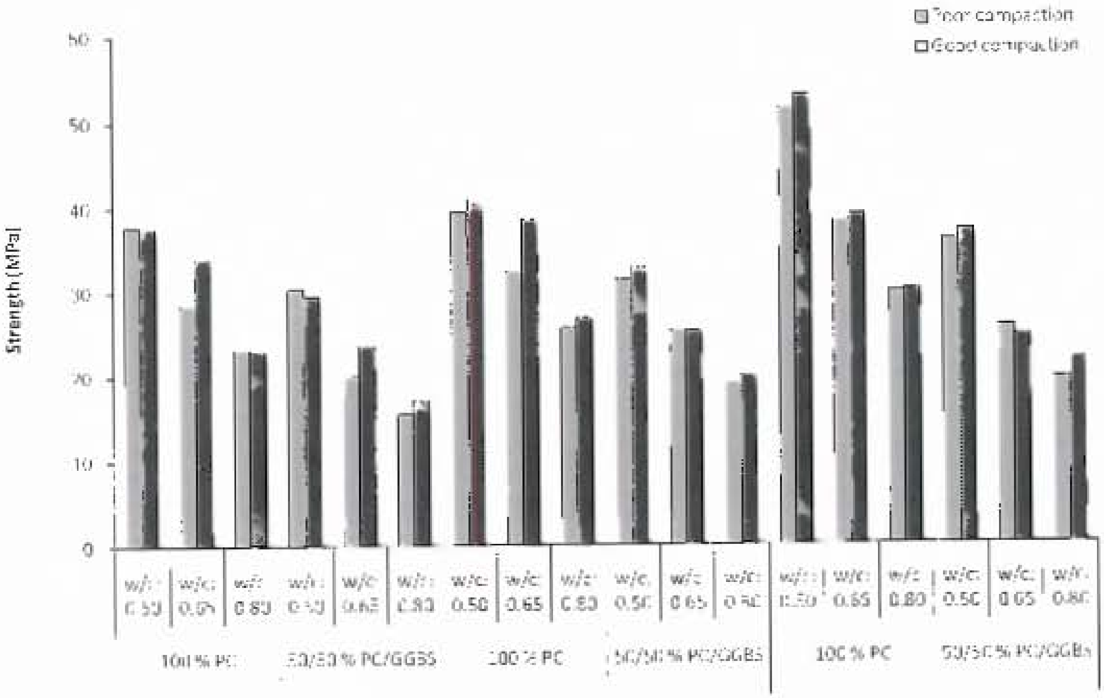
The varied compaction method appeared to give highly varied results. For this reason, the compaction methods were referred to as only compaction methods 1 and 2. The density generally showed the expected trend (viz. better compaction results in a more dense concrete), however, in closer inspection it was concluded that the densities are in fact quite similar, and hence the method used to achieve poorer compaction deemed unsuccessful.

	Poor compaction	**Good compaction**
Summer [35 day]	2311	2333
Summer [90 day]	2314	2344
Winter [40 day]	2361	2366



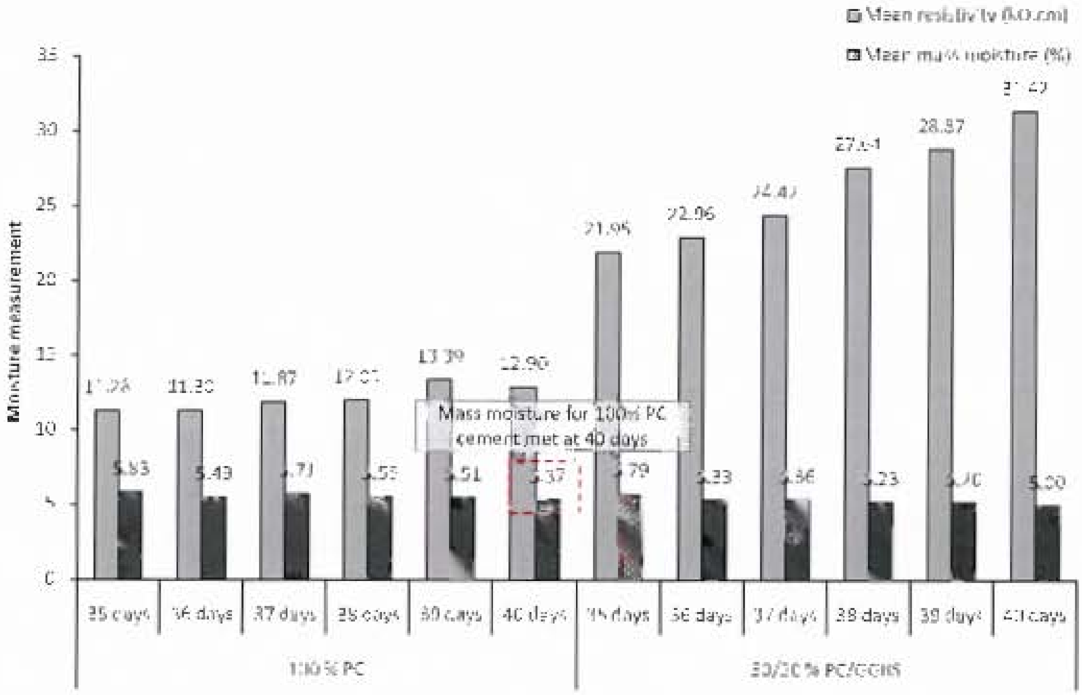
The figures below show the effect of varied compaction on strength and density for all concretes. The results show no clear trend or relationship, and hence the data will not be classified as originally proposed. From Chapter 4 onwards compaction methods shall only be reflected as compaction methods 1 and 2 only.



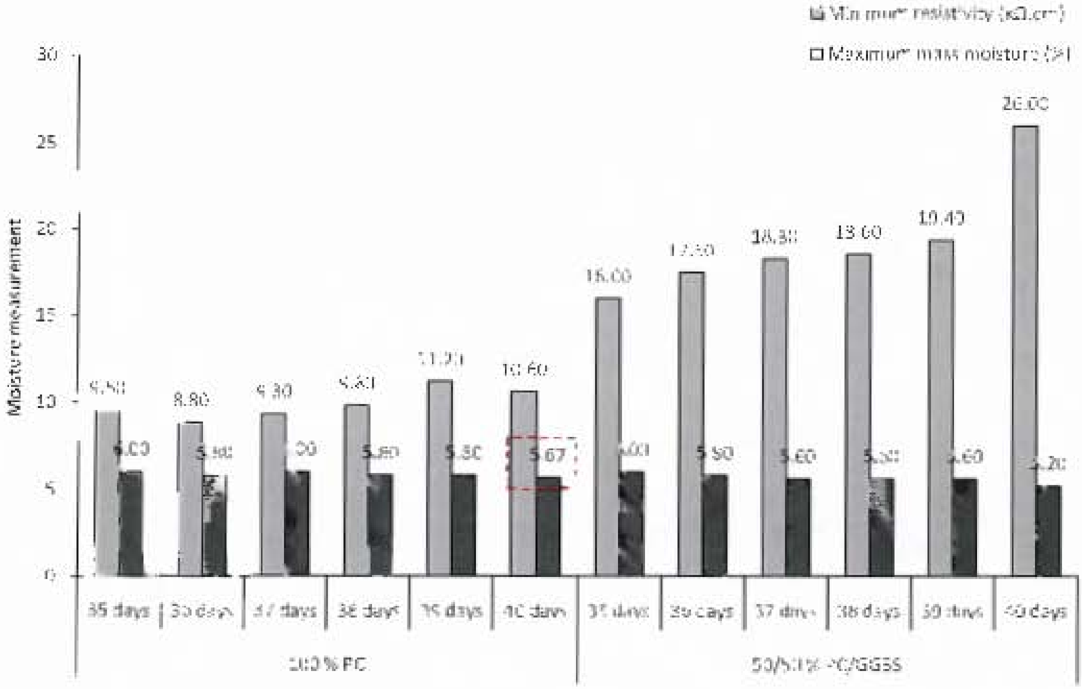


11.4 Moisture monitoring of 40 day winter concrete samples

Mean moisture values for 40 day winter samples:



Minimum electrical resistivity and maximum mass moisture values:



11.5 Multiple linear regression by method of least squares

x1 LN(k-)	x2 m%	y $LN(k_{OPI})$
1.438	4.67	1.595
0.140	4.93	0.911
-1.407	5.00	1.011
0.839	4.60	0.710
2.065	4.20	1.604
1.113	4.60	1.553
2.360	4.07	1.944
2.050	4.27	2.032
-0.217	4.80	1.362
1.627	5.20	1.372
0.755	4.67	1.269
0.155	4.80	1.054
3.214	4.20	2.154
2.511	4.20	2.119
3.247	4.33	2.434
2.342	4.80	2.071
2.930	4.53	1.981
1.070	4.80	2.059
3.850	4.00	2.467
3.480	4.47	2.190
3.917	3.47	2.462
2.645	4.47	2.119
0.835	3.47	1.320
0.026	3.60	1.501
1.020	5.13	1.456
-0.525	3.20	0.792
-0.625	4.80	0.752
1.930	3.80	1.514
0.963	3.67	1.126
1.013	3.60	1.360
1.663	4.00	1.262
1.940	4.13	1.370
1.905	3.93	1.519
1.260	4.47	1.319
1.509	3.87	1.475
-0.299	4.47	1.206
1.028	4.87	1.340
-0.349	4.73	0.855
3.056	3.60	1.963
3.050	4.13	2.067
3.117	4.00	1.863
2.626	3.73	1.849
3.252	4.07	2.452
2.728	3.60	2.224
1.888	3.87	1.463
1.045	4.33	1.516
1.940	4.13	1.373
3.142	4.00	2.049

1. Selection of independent variable terms

x1 = LN(OPI)

x2 = m%

y = LN(k-)

y = a + b . X1 + c . x2

2. Method of least squares to solve for coefficients a, b and c

$$\left\| A \right\| \times \left\| a \right\| = \left\| y \right\|$$

$$\left\| \begin{matrix} n & \Sigma x1 & \Sigma x2 \\ \Sigma x1 & \Sigma(x1)^2 & \Sigma(x1x2) \\ \Sigma x2 & \Sigma(x1x2) & \Sigma(x2)^2 \end{matrix} \right\| \times \left\| \begin{matrix} a \\ b \\ c \end{matrix} \right\| = \left\| \begin{matrix} \Sigma y \\ \Sigma(x1y) \\ \Sigma(x2y) \end{matrix} \right\|$$

3. Solving for known matrix entries

n	83
Σ y	92.35515
Σ x1	-0.5307
Σ x2	379
Σ (x1 y)	200.4102
Σ (x1)²	642.4531
Σ (x1 x2)	109.696
Σ (x2y)	389.3302
Σ (x2)²	1763.756

4. Substituting known matrix terms into least squares matrix equation

$$\left\| \begin{matrix} 83 & 0.5307 & 379 \\ 0.5307 & 642.4531 & 109.70 \\ 379 & 109.70 & 1763.756 \end{matrix} \right\| \times \left\| \begin{matrix} a \\ b \\ c \end{matrix} \right\| = \left\| \begin{matrix} 92.35515 \\ 200.4102 \\ 389.3302 \end{matrix} \right\|$$

5. Solving for the inverse of the A matrix

$$\left\| \begin{matrix} a \\ b \\ c \end{matrix} \right\| = A^{-1} \times \left\| \begin{matrix} 92.35515 \\ 200.4102 \\ 389.3302 \end{matrix} \right\|$$

$$A^{-1} \quad \left\| \begin{matrix} 1.36 & -0.05 & -0.30 \\ -0.05 & 0.00 & 0.01 \\ -0.30 & 0.01 & 0.07 \end{matrix} \right\|$$

5. Final matrix multiplication for constants, b and c

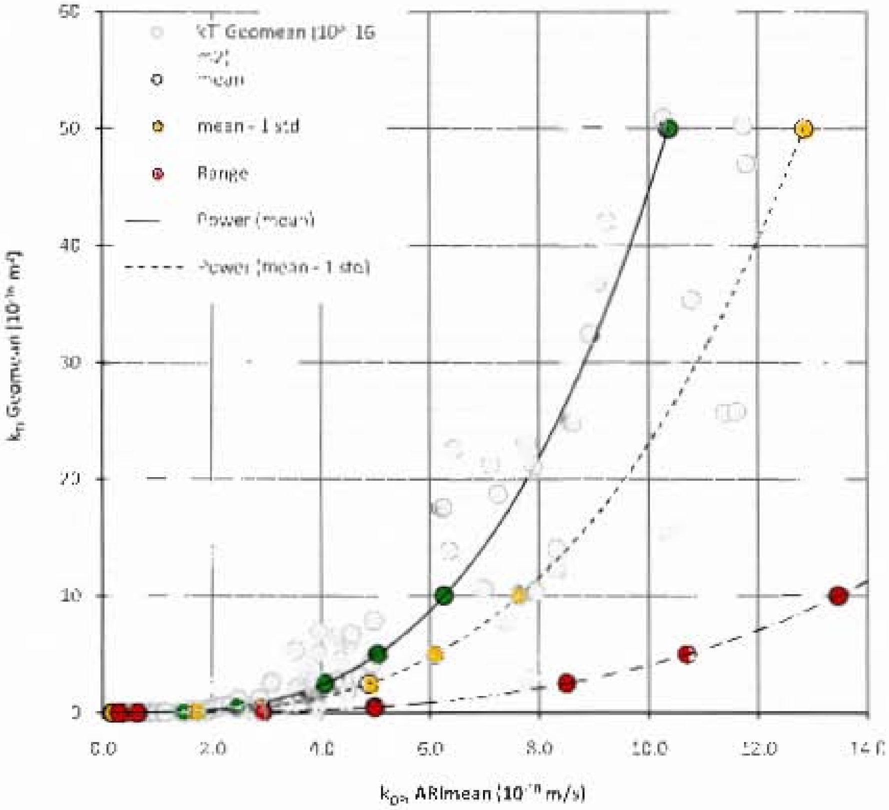
$$\left\| \begin{matrix} a \\ b \\ c \end{matrix} \right\| = \left\| \begin{matrix} 0.763 \\ 0.325737 \\ 0.077 \end{matrix} \right\|$$

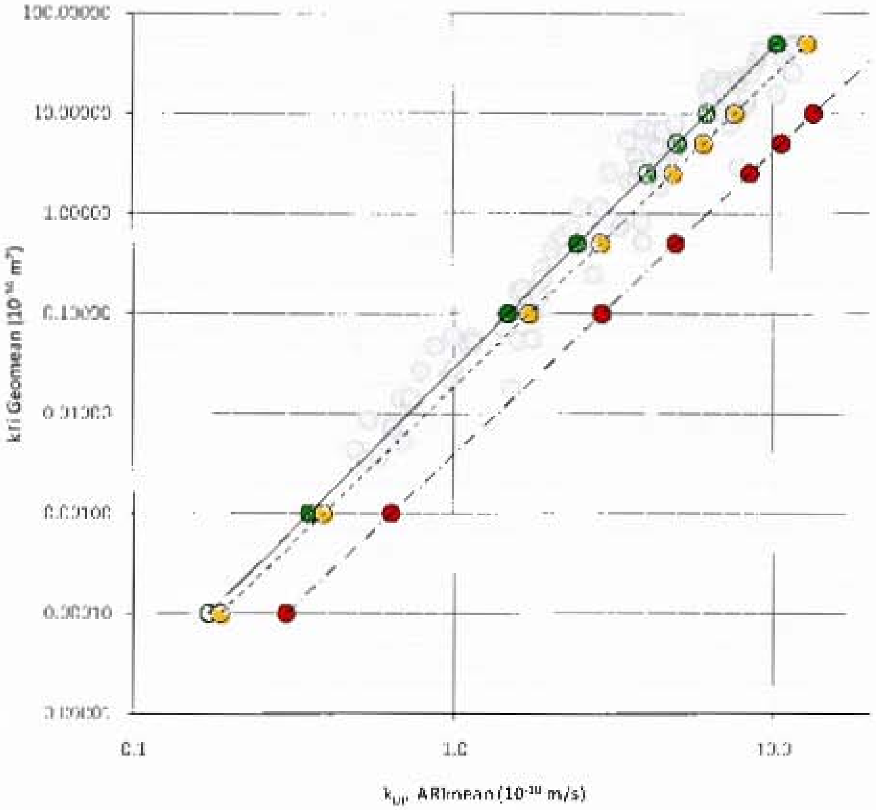
6. Final Correlation: $LN(k_{OPI}) = a + b * LN(k_T) + c * m\%$

x1	x2	y
LN(k_T)	m%	LN(k_{OPI})
2.865	4.40	1.832
3.566	3.47	2.379
2.743	3.87	2.335
3.931	3.27	2.329
3.606	4.13	2.204
-4.924	5.07	-0.440
-4.216	5.20	-0.312
-4.300	5.13	-0.313
3.629	5.47	-0.239
-4.251	5.53	-0.384
-4.742	4.80	-0.613
-5.558	4.93	0.632
-5.241	5.13	-0.365
-5.436	5.20	0.712
-5.602	5.00	0.540
-2.970	5.20	0.145
-3.049	5.00	0.134
-2.827	5.40	0.005
-3.796	5.53	0.038
-3.032	5.33	0.106
-1.704	5.20	0.469
-3.547	4.87	-0.003
-2.850	4.87	0.138
-4.018	5.07	0.415
-2.884	5.20	0.570
-1.519	5.60	0.638
-2.611	5.33	0.359
-1.928	5.53	0.624
-2.061	5.67	0.584
-1.724	5.53	0.495
-0.656	5.07	1.364
-0.629	5.07	0.987
-1.274	4.53	0.635
-2.923	5.07	0.470
-2.264	5.07	0.576

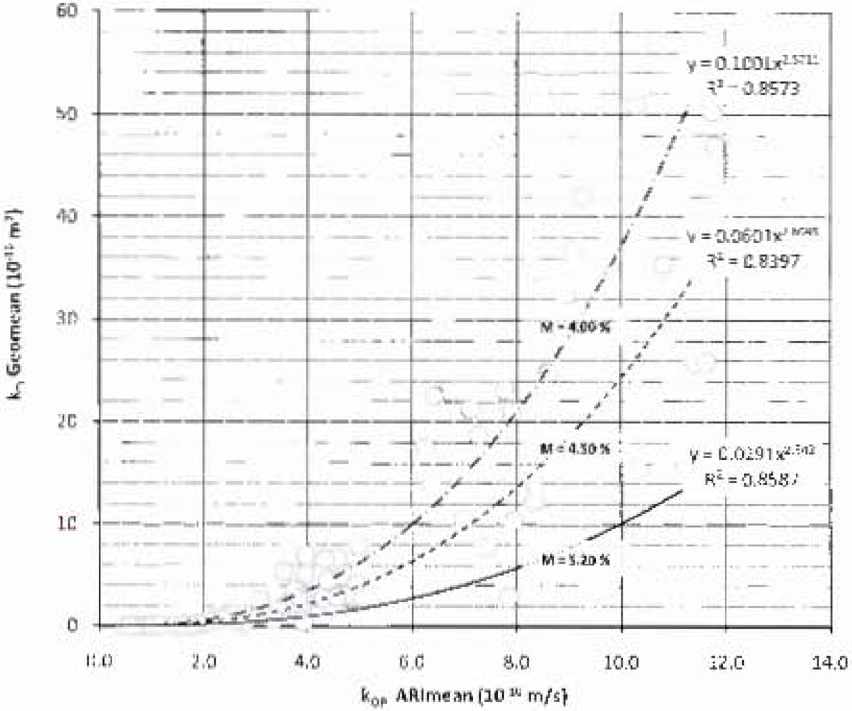
12 APPENDIX E: INTEGRATED APPROACH WORKSHEETS

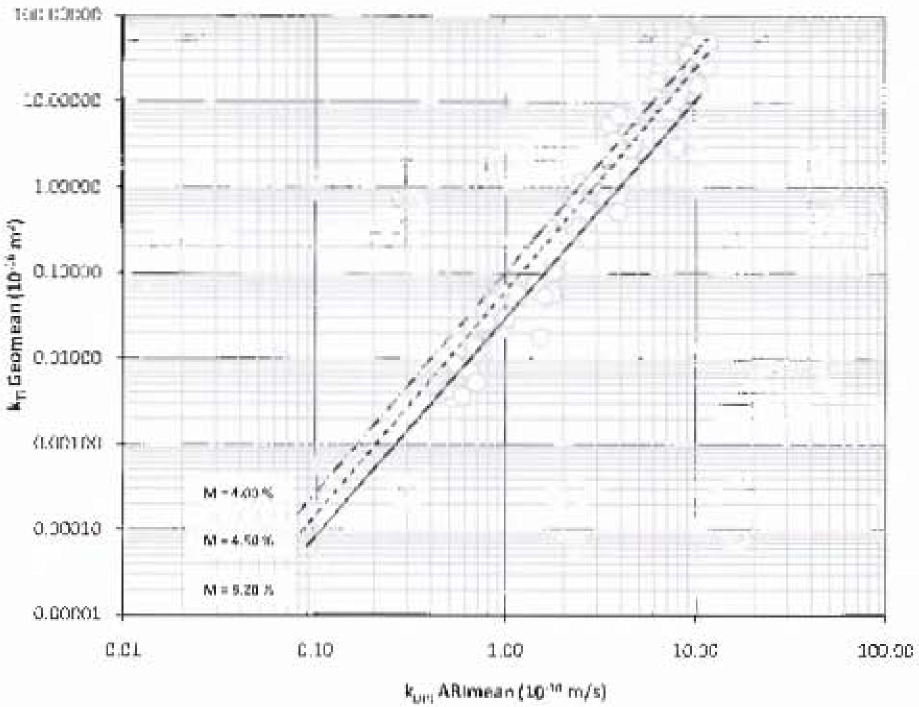
12.1 Full implementation - neglecting moisture influence





12.2 Full implementation - accounting for moisture influence





13 APPENDIX F: ETHICS ASSESSMENT

13.1 EBE Faculty: Assessment of ethics in research projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791).

Students must include a copy of the completed form with the thesis when it is submitted for examination.

This form must only be completed once the most recent revision EBE EiR Handbook has been read.

Name of Principal Researcher/Student: SIMON STARCK Department: EBE

If a Student: Y Degree: MSC.ENG (CIVIL ENG) Supervisor: H.-D. BEUSHAUSEN

If a Research Contract indicate source of funding/sponsorship: CONCRETE MATERIALS AND STRUCTURAL INTEGRITY UNIT

Research Project Title: THE INTEGRATION OF NON-DESTRUCTIVE TEST METHODS INTO THE SOUTH AFRICAN DURABILITY INDEX APPROACH

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	~~YES~~	NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3	~~YES~~	NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	~~YES~~	NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

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

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

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	Signed by candidate	27 MAR 2013

This application is approved by:

Supervisor (if applicable):		
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.		
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions		

ADDENDUM 1:

Please append a copy of the research proposal here, as well as any interview schedules or questionnaires: N/A

ADDENDUM 2: To be completed if you answered YES to Question 2: N/A

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf) in order to be able to answer the questions in this addendum.

2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc) or legally restricted groups?	YES	NO
2.3 Will you not be able to secure the informed consent of all participants in the research? (In the case of children, will you not be able to obtain the consent of their guardians or parents?)	YES	NO
2.4 Will any confidential data be collected or will identifiable records of individuals be kept?	YES	NO
2.5 In reporting on this research is there any possibility that you will not be able to keep the identities of the individuals involved anonymous?	YES	NO
2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 3: To be completed if you answered YES to Question 3: N/A

3.1 Is the community expected to make decisions for, during or based on the research?	YES	NO
3.2 At the end of the research will any economic or social process be terminated or left unsupported, or equipment or facilities used in the research be recovered from the participants or community?	YES	NO
3.3 Will any service be provided at a level below the generally accepted standards?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 4: To be completed if you answered YES to Question 4: N/A

4.1 Is there any existing or potential conflict of interest between a research sponsor, academic supervisor, other researchers or participants?	YES	NO
4.2 Will information that reveals the identity of participants be supplied to a research sponsor, other than with the permission of the individuals?	YES	NO
4.3 Does the proposed research potentially conflict with the research of any other individual or group within the University?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues: