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ASSESSMENT OF IN-SERVICE DURABILITY PERFORMANCE OF NATURAL DRAFT COOLING TOWERS IN A PETROCHEMICAL ENVIRONMENT

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DECLARATION

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ABSTRACT

Effective temperature control is an important operation requirement in petrochemical processes, where Cooling Towers (CT) play a key role in efficiently lowering water temperature for reuse in various chemical processes. Natural draft cooling towers function as heat extraction systems, dissipating thermal energy from hot water into the atmosphere through cold air. However, many reinforced concrete cooling towers have exhibited signs of deterioration over time, such as cracking, corrosion, and structural misalignment, posing the risk of structural failure.

To address these issues, structural condition assessment programs, aiming to inspect, repair, and monitor cooling towers to prevent structural collapse are of significant importance. The focus of this study investigates the durability of natural draft cooling towers in an aggressive petrochemical environment. With a focus on Sasol Secunda Natural Draft Cooling Towers, the research aims to identify and characterize the various concrete deterioration mechanisms, quantify durability parameters, and explore mitigation measures for both new and existing cooling towers.

Concrete deterioration is a significant concern in structures exposed to harsh environments, affecting their global stability and service life. The study examines the role of cover concrete quality in resisting corrosive agents and assesses durability using South Africa's three durability index (DI) tests, including water sorptivity, chloride conductivity, and oxygen permeability.

The study comprised of on-site assessments and laboratory testing methods to determine the durability performance of cooling towers. The approach includes the three durability index tests. On-site assessments include visual inspections and non-destructive testing (NDT) near areas displaying signs of deterioration.

The significance of this research relies on the operational efficiency of cooling towers in petrochemical plants, their vulnerability to harsh conditions, and the need for durability design considerations at Front End Loading (FEL) engineering and planning. It aims to shift from prescriptive to performance-based design approaches and provide insights for maintenance and mitigation strategies.

This study contributes to the knowledge of concrete durability in challenging environments, aiming to enhance the longevity and performance of critical industrial infrastructure, particularly natural draft cooling towers.

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CONTENTS

List of Abbreviations

Abbreviation	Meaning
CT	Cooling Tower
DI	Durability Index
OPI	Oxygen Permeability Index
CCI	Chloride Conductivity Index
WSI	Water Sorptivity Index
LCSI	Leaching Corrosion Sub Index
SCSI	Spalling Corrosion Sub Index
ITZ	Interfacial Transition Zone
NDT	Non-Destructive Testing
SLP	Service Life Prediction
OCI	Overall Corrosion Index
AI	Aggressiveness Index

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1. INTRODUCTION

1.1 Background

In the context of petrochemical factory processes, an essential performance requirement is precise temperature control. Cooling Towers (CTs) efficiently dissipate heat from circulating water before it returns to the factory for its designated functions. Given the impracticality of using hot water in the various processes of a petrochemical plant, cooling towers become necessary. Essentially, a cooling tower operates as a heat extraction system, removing excess thermal energy from hot water and releasing it into the atmosphere using cold air (Afshari & Dehghanpour, 2019).

Over time, many reinforced concrete cooling towers in power generation and chemical plants have displayed signs of damage and deterioration, including cracking, misalignment of structural components, corrosion of reinforcing steel, spalling and delamination of concrete, deflection of tower components, and differential settlement of foundations, resulting in global tilting of the towers (Bamu & Zingoni, 2005).

To address these issues, structural condition assessment programs have been developed aimed at inspecting, repairing, and monitoring the behaviour of cooling towers (Bamu & Zingoni, 2005). These defects, whether individually or collectively, can eventually lead to structural collapse under serviceability limit conditions.

This research investigates the in-service durability performance and deterioration mechanisms of the external surface zone of a natural draft reinforced concrete cooling tower operating in a harsh petrochemical environment. The study focuses on the Sasol Secunda Natural Draft Cooling Towers located within a petrochemical production plant in Mpumalanga, South Africa. The Sasol Secunda Natural Draft Cooling Towers were selected for this study due to their industrial significance, observed deterioration, accessibility for data collection and representativeness of cooling towers in petrochemical environments. The towers are essential for temperature control in the petrochemical plant, but they exhibit signs of deterioration, such as cracking, corrosion, and structural misalignment. This study aims to investigate the durability of these towers and provide recommendations for their maintenance and repair.

The assessment involves visual inspections of the cooling tower structure, detailed visual assessment of extracted core samples, and laboratory measurements of the fluid-flow properties of the near-surface zone of the concrete. The research aims to identify the causes of deterioration and provide recommendations for improving the durability and longevity of these critical industrial structures.

Prior research has highlighted the need for longer service lives due to their critical role in the petrochemical industry (Harte & Krätzig, 2001). Therefore, durability considerations must be integrated into the early design phases of such projects. Researchers and industry professionals are exploring potential measures, such as employing special high-performance concrete made of densely packed aggregate and cement combined with fly ash and micro silica, to enhance the long-term durability of concrete against chemical attack (Harte et al 2001). These measures aim to extend the service life of concrete structures in aggressive environments, such as those found in petrochemical plants. Chemical production plants such as Sasol are under scrutiny for their elevated emissions of contaminants into the atmosphere, necessitating the usage of cleaner technologies (Ropital, 2009). Petrochemical factories create harsh exposure conditions that increase the risk of reinforcing steel corrosion in concrete structures.

Concrete infrastructure undergoes deterioration over its service life, which can significantly impact its stability, structural capacity, and integrity, potentially leading to severe consequences. The deterioration of concrete structures is closely linked to the penetration of harsh pollutants and subsequent corrosion of the reinforcing steel. Corrosion occurs after aggressive agents have breached the concrete cover layer. The quality of the cover concrete layer plays a vital role in the durability of concrete, especially in resisting the ingress of corrosive chemicals (Alexander et al., 2008).

This research will focus on Natural Draft Cooling Towers using water, which may be contaminated, as a cooling medium. Within petrochemical refineries, the contamination of water can arise from various sources during the refinery process, such as equipment leaks and oil spillages. This contaminated water is reintroduced into the process system and subsequently recirculated to the cooling tower for temperature regulation. The utilization of process water introduces inherent risks to the structural integrity of the tower, attributable to the chemical composition of the medium, which harbours deleterious agents including sulphides, ammonia, suspended solids, and chlorides (Reddy et al., 2020). All of these agents pose detrimental consequences to reinforced concrete structures.

To assess durability performance and ensure the quality of concrete structures, South Africa (SA) has developed three durability index (DI) tests. These tests measure water sorptivity, chloride conductivity, and gas permeability, all of which relate to the transport mechanisms in concrete. The DI serves as a guide to specify the required concrete quality in a particular environment to prevent aggressive environmental ingress. Additionally, the DI enables the prediction of service life through the development of service life prediction models (Alexander et al., 2008). Once the durability parameters are quantified against the index, they can be used to establish construction specifications (concrete mix designs) to achieve the desired concrete quality for a specific application and environment.

1.2 Significance of the Study

The operational efficiency of cooling towers (CTs) in petrochemical plants and power generation facilities is paramount, as they provide essential cooling water for critical processes. However, the harsh environmental conditions within these facilities exert detrimental effects on CT operational performance and durability. Existing degradation mechanisms and their impact on CT lifespan remain poorly understood. Therefore, this study investigates the durability characteristics influencing the Sasol Secunda Natural Draft Cooling Towers, located in Mpumalanga South Africa, and explains the deterioration mechanisms that compromise their performance and longevity. This understanding will inform strategies for optimized design, material selection, and maintenance practices, ultimately promoting the sustainable operation of CTs in harsh industrial environments. This study contributes to the knowledge of concrete durability in challenging environments, aiming to enhance the longevity and performance of critical industrial infrastructure, particularly natural draft cooling towers, and provides valuable insights for improving durability design considerations in future projects.

The results derived from this research will provide the basis for planning of maintenance interventions, developed with the objective of extending the operational service lives of these important plant structures, particularly cooling towers.

The insights collected from this study will serve as a valuable resource for plant owners reliant on the uninterrupted functionality of these critical infrastructure components. This study is significant because it allows plant owners to cultivate enhanced maintenance practices and utilize advanced tools for the sustained maintenance and durability of vital civil infrastructure operating within harsh environmental exposures.

1.3 Aim and Objectives of the Study

The aim of this research study is to gain insight into the in-service durability performance and deterioration mechanisms affecting natural draft reinforced concrete CTs that are operating in harsh petrochemical environments.

The objectives of this study include:

1. Conducting preliminary site investigations to assess the current condition of the Sasol Secunda Natural Draft Process Water Cooling Tower through visual inspections, with the aim of identifying areas of concern.
2. Examining the influence of harsh environmental exposure on the Sasol Secunda reinforced concrete Natural Draft Cooling Towers.
3. Identifying and analysing deterioration mechanisms particularly relevant to natural draft cooling towers employing contaminated water as a cooling medium.
4. Assessing the durability parameters of the as-built Sasol Secunda Cooling Towers using the Durability Index approach, aimed at quantifying the extent of their resistance to harsh conditions.

1.4 Scope and Limitations

The scope of this research project entails an in-depth investigation into the various deterioration mechanisms affecting reinforced concrete structures, with a particular focus on natural draft cooling towers situated within process and power generation plants. To accomplish this objective, a comprehensive review of existing literature will be conducted, scrutinizing the various modes of concrete deterioration and their underlying causes.

Following this literature review, a preliminary site investigation will be executed, serving as a foundational visual assessment mechanism. This visual assessment will play a pivotal role in pinpointing areas of defective concrete, which will subsequently serve as test specimens for rigorous laboratory investigations.

Upon the identification and demarcation of the defective concrete locations, core samples will be extracted from different positions on the cooling towers situated at the Sasol petrochemical facility in Secunda, South Africa. The core extraction process will encompass multiple locations on the same elevation level and will be replicated at varying heights along the tower structure. This strategic approach is intended to yield core samples that collectively provide a comprehensive and holistic understanding of the diverse deterioration mechanisms established throughout the entirety of the tower shell.

This study is limited by the reliance on visual inspection from grade and durability index testing on existing concrete for assessing the condition of the cooling towers. While these methods provide valuable insights, they may not capture all aspects of concrete deterioration, particularly in aged structures like the cooling towers at the Sasol Secunda facility. The durability index tests, namely water sorptivity, chloride conductivity, and oxygen permeability, are primarily designed to assess the durability of new concrete. Their application to existing structures, especially those exposed to aggressive environments for extended periods, may not fully account for the complex and often localized nature of deterioration. The tests may not adequately capture the effects of cracking, leaching, or other forms of degradation that have developed over time. Therefore, the results should be interpreted with caution and considered alongside other forms of assessment, such as visual inspection, petrographic analysis, and in-situ testing

Additionally, the study is limited by the availability of historical data, which may not fully reflect the environmental conditions and maintenance history of the towers. This lack of comprehensive data could hinder a complete understanding of the factors that have contributed to the observed deterioration. The accuracy of the findings may be affected by these limitations.

Despite these constraints, the research aims to provide valuable insights into the deterioration mechanisms affecting reinforced concrete structures, particularly natural draft cooling towers, contributing to the broader understanding of concrete durability in challenging industrial environments.

1.5 Report Structure

The report is structured into five chapters as outlined below:

Chapter 1: Introduction

The first chapter introduces the scope of the study topic and provides background information on concrete technology, concrete durability and concrete deterioration mechanisms. This chapter also outlines the aim and objectives of this study, supported by an explanation of the research topic's significance.

Chapter 2: Literature Review

The second chapter contains a comprehensive literature review, which includes an in-depth exploration of the durability performance of reinforced concrete in harsh exposure environments. It examines the factors influencing concrete durability, the relevance of natural draft cooling towers to the petrochemical industry, and how concrete durability impacts their performance. Additionally, this chapter examines the concrete deterioration mechanisms typically observed in mature or aged structures.

Chapter 3: Methodology

The third chapter contains the research methodology, which outlines how the desired study outcomes will be achieved. This chapter describes the research approach that was employed and describes the necessary assessments and procedures that were followed during this study.

Chapter 4: Results and Discussion

The fourth chapter contains the results of this study, an analysis of the results and further discussion based on the experimental investigations conducted.

Chapter 5: Conclusion and Recommendations

The fifth and final chapter serves as the conclusion of the research project. It discusses the various deterioration mechanism in natural draft cooling towers within petrochemical or power generation plants. Additionally, this chapter provides recommendations for further research and additional studies, shedding light on potential areas of interest and exploration in the field.

2. LITERATURE REVIEW

2.1 Introduction

Reinforced concrete remains the dominant construction material for today's infrastructure, and its current formulations are expected to maintain their reputation for the foreseeable future (Collis, 2021). However, concrete's susceptibility to degradation and environmental impact necessitates the development of more durable and sustainable alternatives for future generations. (Collis, 2021).

Despite considerable advancements in understanding the nature of concrete and the factors influencing its durability, modern concrete structures exhibit a higher prevalence of durability-related issues compared to half a century ago, as noted by Mehta (1991). The premature deterioration and subsequent repair of these structures has led to significant financial repercussions for the economies of many countries (Arya and Newman, 1990). Consequently, there exists a pressing need to address concerns related to concrete durability and ensure the enduring resilience of concrete structures. Whilst it may be unrealistic to expect concrete to remain unscathed for over a century without maintenance, there is no justification for extensive structural degradation after only a few years of service (Scott, 1997).

It is essential to emphasize that durable concrete equates to high-quality concrete. In turn, a high-quality concrete, is one that achieves its intended performance expectations throughout its designed service life. Achieving this desired level of quality necessitates an understanding of concrete durability, the factors influencing it, and informed outlooks on the mechanisms underpinning deterioration (Basson, 1989). The graph, as illustrated in Figure 2.1, presents two distinct structures, denoted as structure A and B. In this graphical representation, structure A undergoes a gradual deterioration process, ultimately reaching its intended design service life without necessitating any unprepared rehabilitation and/or maintenance interventions. Conversely, structure B exhibits a more rapid rate of deterioration, compelling unplanned interventions to extend the structure's intended design service life, as explained by Beushausen, H., Otieno, M., and Alexander, M.G. (2021).

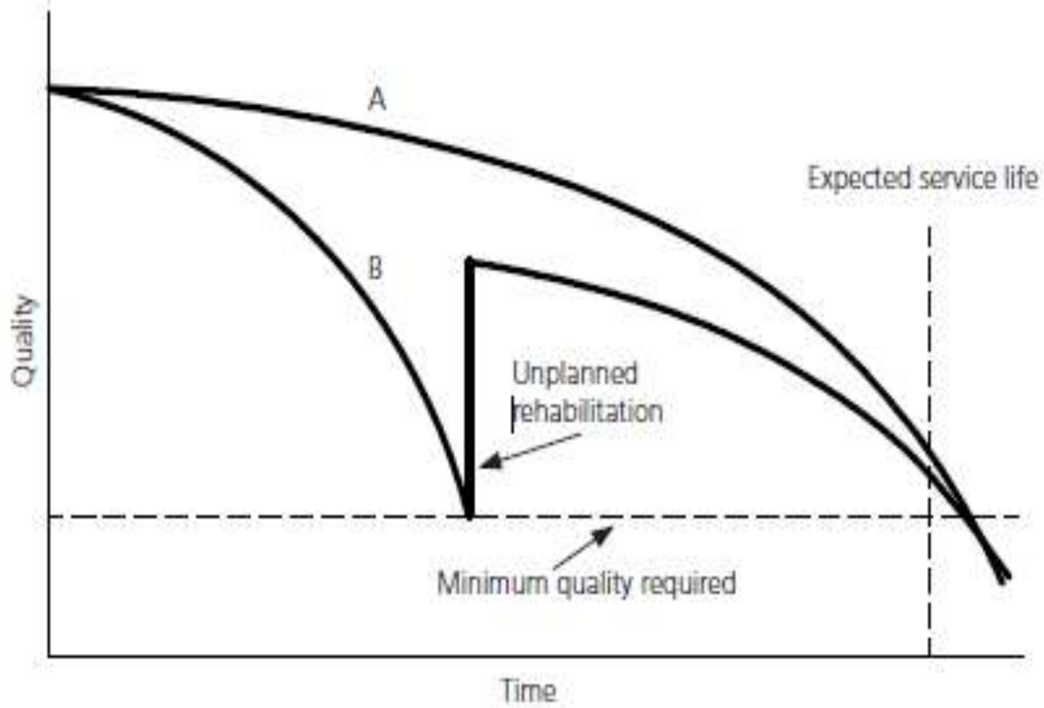

Figure 2-1: Two Scenarios of Deterioration and Rehabilitation (Beushausen et al, 2021)

The accelerated deterioration observed in structure B raises concerns of unexpected degradation, which could potentially lead to the decommissioning of a critical structure. To pre-empt such consequences, it becomes imperative to develop the capability to predict a structure's deterioration. Achieving this predictive capacity hinges upon a comprehensive understanding of both the concrete quality and the exposure environment to which the structure is subjected. This knowledge is essential in ensuring that the desired design service life of the structure is achieved. Unfortunately, in modern construction practices, the oversight of durability design considerations has caused premature deterioration in numerous structures. This phenomenon of premature deterioration imposes substantial operational and capital costs associated with the rehabilitation of these structures to a suitable and safe state. As suggested by Beushausen et al. (2021), modern-day concrete practices are progressively transitioning away from conventional prescriptive design models toward performance-based design approaches in the realm of durability design. These alternative approaches will be expounded upon in greater detail in subsequent chapters.

Within the framework of performance-based design, designers assume the responsibility of defining a suitable degree of durability performance for a structure within a given exposure environment. Subsequently, they formulate their designs in alignment with a defined set of performance parameters. Importantly, the construction contractor bears the responsibility of ensuring that the designed structure adheres to the approved for construction (AFC) drawings, approved by the responsible design engineer. Furthermore, the contractor must demonstrate strict adherence to the designer's technical specifications, which encompass durability parameters, as well as compliance with stipulated quality requirements.

2.2 Concrete Durability in Cooling Towers

Concrete, when designed and cast appropriately, is acknowledged as a durable construction material that can deliver an extended service life under normal exposure conditions. Over time, all concrete structures will experience some degree of deterioration. However, the rate of degradation can be managed through the design and casting of high-quality concrete. Nevertheless, there are instances where structures deteriorate at an accelerated pace, necessitating repair work to restore them to their original condition (Beushausen & Louw, 2021).

Durability of concrete is defined as the capacity of a reinforced concrete (RC) structure to withstand aggressive environmental loads while maintaining its original design functionality at an acceptable level (Demis & Papadakis (2019). Achieving durability is contingent on sound design principles, judicious material selection, meticulous construction practices, and timely maintenance interventions. The incorporation of durability considerations into the project's conceptual phase is pivotal to ensure that the structure attains its intended service life without succumbing to premature deterioration. It should be noted that steel corrosion is not the sole mechanism of deterioration, and other mechanisms pertinent to the degradation of reinforced concrete cooling towers will also be scrutinized. These mechanisms are frequently linked to incorrect construction procedures, inadequate steel reinforcement cover, and unsuitable mix designs for the intended purpose, all of which can be managed and incorporated into a structured durability design process addressing durability-related concerns.

Durability factors encompass conditions that aid in the ingress of deleterious substances into the concrete substrate. These factors include various parameters, including the quality of the aggregate, cement content in the concrete mix, water quality, compaction and curing procedures, and the permeability of the concrete (Kropp & Alexander, 2007). External factors that influence concrete durability encompass moisture levels, temperature variations, carbon dioxide and chloride ingress, wetting and drying cycles, freeze-thaw cycles, and exposure to sulphate attacks, among others. Concrete must be designed to withstand all service conditions, encompassing its resistance to both applied loads and its exposure to aggressive environmental factors.

Concrete's durability is demonstrated by some of the world's oldest concrete structures that endure to this day. These historic structures have withstood the test of time which emphasizes the longevity of concrete when appropriately designed. Notably, these structures often utilized materials with pozzolanic properties that strengthened their durability. In modern-day constructions employing ordinary Portland cements, it becomes evident that concrete may be susceptible to deterioration within harsh exposure environments. Deterioration can manifest in the degradation of the concrete matrix itself and in the corrosion of embedded reinforcing steel, affecting both new and existing structures. It is essential to grasp that durability is not solely contingent on concrete properties but is also contingent on concrete performance throughout its service life. A crucial point of consideration is that concrete exhibits distinct behaviours in changing exposure environments, with environmental conditions having a significant influence on durability performance, resulting in varied responses across different environments.

In the context of natural draft concrete cooling towers, it is common practice to utilize water contaminated with hydrocarbons as part of the cooling process. Sulphides, ammonia, suspended solids, and chlorides are among the contaminants present in the water (Reddy et al, 2020). This water is stored in a cooling tower pond and subsequently evaporates into the atmosphere as it passes through the tower. The utilization of process water introduces inherent risks to the structural integrity of the tower, attributable to the chemical composition of the medium, which harbours deleterious agents including sulphides, ammonia, suspended solids, and chlorides (Reddy et al., 2020). All of these agents pose detrimental consequences to reinforced concrete structures.

2.2.1 Cooling Tower Structures

Natural draft cooling towers are primarily designed as thin-shell structures constructed using reinforced concrete (RC). These shells are supported along their perimeters by an arrangement of columns. In comparison to the tower's height, these columns typically constitute less than 10% of the total tower height. The columns vary in design and shape, resting either on single pad footings or on a ring beam foundation supported by a piling system (Niemann et al., 1986).

The type of cooling system used can vary, with options including a water distribution system equipped with splash grids or the use of heat exchangers. Regardless of the cooling system choice, they rely on an arrangement of beams and columns for support. However, it is imperative to note that the shell of the cooling tower demands the most precise attention to detail in both its design and construction.

Figure 2.2, illustrated below, shows the evolutionary development of cooling towers over the years. The expansion in the size of cooling towers is fundamentally linked to the generating capacity of the power or petrochemical generating plant they serve. As generating capacity increases, the necessity to enlarge cooling towers becomes evident due to the increased demand for cool water essential for the efficient operation of these plants.

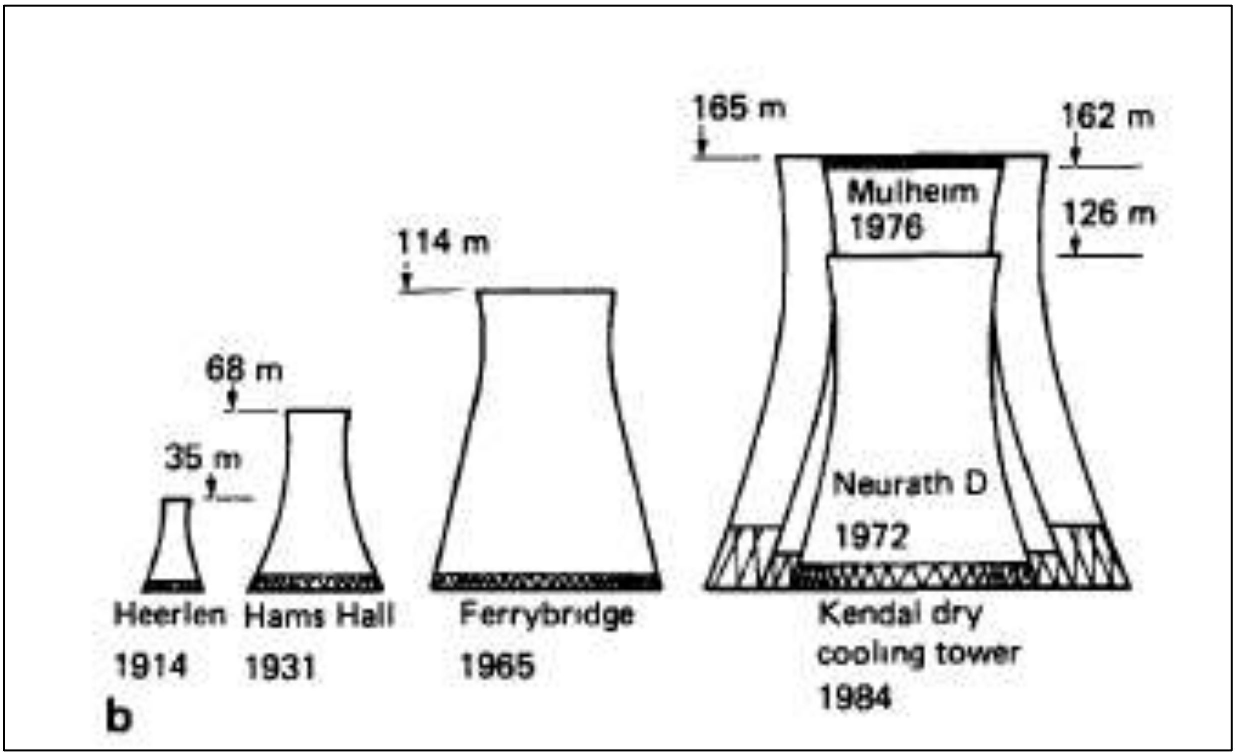

Figure 2-2:Increase in Size of Cooling Towers over the years (Niemann et al, 1986)

2.2.2 Types of Cooling Towers

A cooling tower is an architectural structure designed to expel waste heat into the atmosphere. This cooling process involves reducing the temperature of a water supply, rendering it suitable for subsequent reuse. The utilization of cooling towers offers the distinct advantage of avoiding the requirement for a constant water supply, requiring makeup water solely in response to losses incurred. Consequently, cooling towers can be advantageously implemented in regions struggling with water scarcity concerns. Within the domain of natural draft cooling towers, two distinct cooling methods are commonly employed: dry cooling and wet cooling systems. These structures are critical for maintaining the operational integrity and safety of a wide range of industries, including power generation plants, chemical manufacturing facilities, petroleum refineries, and more. This introduction highlights the paramount importance of cooling towers in these contexts and underscores their significance in achieving sustainable and cost-effective heat dissipation solutions.

Cooling towers are necessary components in industrial and thermal power locations, serving as a connection in the sequence of efficient heat management. They contribute to the safe and sustainable operation of petrochemical industries and power plants by dissipating excess heat, conserving resources, enhancing energy efficiency, and ensuring the longevity of equipment. As the demand for industrial and power generation capacities continue to grow, the importance of cooling towers in assisting these operations becomes increasingly important for economic, environmental, and safety reasons.

2.2.2.1 Mechanical Draft Cooling Towers

Mechanical draft cooling towers are components in petrochemical processes and power generation plants due to their ability to efficiently dissipate excess heat. At the core of their operation lies the utilization of forced air movement, a mechanism that enhances heat transfer and overall cooling tower performance.

Mechanical draft cooling towers use large fan systems to create forced air movement within the tower structure. These fans are typically axial or centrifugal, designed to generate the required airflow for effective heat exchange (Aung & Bhattacharya, 2019).

Mechanical draft cooling towers are known for their high heat dissipation efficiency due to the controlled and directed forced air movement, resulting in efficient heat transfer (Li et al., 2017). Research by Wu et al. (2018) indicates that mechanical draft cooling towers consume energy mainly for fan operation, making the choice of fan type and control systems important for energy efficiency.

Mechanical draft cooling towers find applications in a wide range of industries, including:

- Power generation plants (Gupta et al., 2019)

- Petrochemical refineries (Rao & Reddy, 2020)
- HVAC systems in commercial buildings (Liu et al., 2018)

Mechanical draft cooling towers are designed to reduce the consumption of water by promoting recirculation, aligning with the increasing focus on water conservation in the industry as a whole (Pandey & Mishra, 2017).

In mechanical draft cooling towers, mechanical instruments are used to circulate the air. Equipment such as fans or blowers are used. The two types of mechanical draft towers are forced and induced draft cooling towers. These two methods of mechanical draft towers differ only with the position of the equipment that circulates the air. In a forced draft tower, the equipment is installed at the bottom of the tower, whereas the induced draft towers equipment is situated at the top of the tower.

Mechanical draft cooling towers, with their use of forced air movement, enable an efficient solution for heat dissipation in petrochemical and power generation processes. Their design elements and performance characteristics make them adaptable and reliable components in various applications. Understanding their operation and optimizing their design and operation are essential for achieving energy efficiency, environmental compliance, and overall system performance.

2.2.2.2 Natural Draft cooling towers

Natural draft cooling towers, characterized by their distinctive hyperbolic shape and towering chimney stacks, constitute a critical component in various industrial processes and thermal power generation facilities. Central to their operation is the reliance on natural convection as the primary mechanism for efficient heat dissipation, making them an integral part of heat management processes.

Natural draft cooling towers are recognized for their distinctive hyperbolic shape, which enhances the stack effect and promotes the upward flow of air (Shah et al., 2018). Tall chimney stacks facilitate the establishment of a strong draft allowing for the removal of heated air and moisture (Kumar et al., 2017). Natural draft cooling towers utilize buoyancy within a tall hyperboloid tower, a central point of this research. These hyperboloid cooling towers are distinctive features of natural draft cooling systems due to their structural strength and capacity to enhance airflow acceleration within the tower, thereby enhancing cooling efficiency. In this type of cooling tower, hot water is pumped to a specified design height before entering the tower, where it is distributed over the fill. The sprayed water drops on and encounters the cooler ambient air, initiating the cooling process. The warmed, moist air rises due to its lower density compared to the drier, cooler external air. This density difference drives the warm air out through the tower's top, while the cooled water droplets settle into the pond at the tower's base (Glasstone, 1994).

Inside these cooling towers, fill media are employed to facilitate the exchange of heat between the incoming hot water and the upward-rising air (Li et al., 2020). Natural draft cooling towers are recognized for their exceptional heat rejection efficiency, owing to the large surface area of the fill media and the height of the chimney stack (Li et al., 2020).

Research by Kumar et al. (2017) reveals that natural draft cooling towers consume minimal energy compared to mechanical draft counterparts, as they rely predominantly on natural convection.

Natural draft cooling towers find applications in various industries and thermal power plants due to their efficiency and reliability:

- Large-scale power generation facilities (Dong et al., 2019)
- Petrochemical refineries (Xu et al., 2016)
- Iron and steel manufacturing (Shah et al., 2018)

Natural draft cooling towers are heavily reliant on natural convection for heat dissipation and are indispensable components in industrial and thermal power generation contexts. Their distinctive design characteristics and exceptional performance attributes make them an efficient and sustainable solution for heat management. Understanding the principles of their operation and optimizing their design are necessary for energy efficiency, environmental sustainability, and overall system performance.

2.2.3 Deterioration effects of process waters in cooling towers

Reinforced concrete (RC) is a popular choice for cooling tower construction due to its cost-effectiveness. However, the presence of ionic species in process waters can trigger a multitude of deterioration mechanisms, significantly impacting the structural integrity and service life of these structures.

Chlorides are a primary concern, promoting the depassivation of embedded steel reinforcement. Chloride ingress disrupts the high pH, alkaline environment within the concrete pores, destabilizing the protective oxide film on the steel surface. This facilitates the initiation and propagation of corrosion.

Concrete deterioration poses a significant concern for the durability and longevity of reinforced concrete structures, particularly in industrial settings like cooling towers where recycled water is used. The presence of ions such as chlorides and sulfates in the water can initiate chemical reactions that lead to the corrosion of steel reinforcement and the degradation of the concrete matrix itself. This can result in reduced structural strength, cracking, and ultimately, the failure of the structure.

Khaloo et al. (2024) investigated the impact of various water-soluble ions on the corrosion of reinforced concrete in a steel manufacturing plant. While their study focused on a steel manufacturing plant, the findings are relevant to natural draft cooling towers in petrochemical plants due to the similar exposure to harsh water conditions. The study identified several key deterioration effects of ionic species in water:

- **Chloride ions (Cl-)**: These ions are highly detrimental to reinforced concrete structures. They penetrate the concrete's protective layer and initiate the corrosion of steel reinforcement bars. This corrosion process leads to the formation of iron oxides, which expand in volume compared to the original steel. This expansion creates internal stresses within the concrete, leading to cracking, spalling, and overall weakening of the structure.
- **Sulfate ions (SO4^2-)**: Sulfate ions react with the cement hydration products in concrete, forming expansive compounds. These compounds increase in volume, generating internal pressure that can cause extensive cracking and disintegration of the concrete. This damage not only weakens the concrete itself but also exposes the steel reinforcement to further corrosion, accelerating the deterioration process.
- **Magnesium ions:** While magnesium ions do not directly corrode steel, they can exacerbate the harmful effects of other ions like chlorides. Magnesium ions can displace calcium ions in the cement matrix, which is essential for the concrete's strength and durability. This displacement weakens the concrete's structure, making it more susceptible to chloride penetration and subsequent steel corrosion.

- **Ammonium ions:** These ions can trigger a series of chemical reactions that lead to the formation of acids within the concrete. These acids can dissolve the cement matrix, weakening the concrete's structure. Additionally, they can corrode the steel reinforcement, further compromising the structural integrity of the cooling tower.
- **Nitrate ions:** Although nitrate ions are not directly corrosive to steel, they can indirectly contribute to concrete deterioration. They can stimulate the growth of certain types of bacteria that produce acids. These acids can then attack both the concrete matrix and the steel reinforcement, leading to structural damage.
- **Phosphate ions:** These ions can react with calcium ions in the cement matrix, forming calcium phosphate compounds. In moderate concentrations, these compounds can fill the pores within the concrete, potentially reducing its permeability to other harmful ions. However, excessive phosphate concentrations can lead to the formation of expansive compounds that can damage the concrete.
- **Carbonate ions:** Carbonate ions are naturally present in water and can react with calcium ions in the cement to form calcium carbonate. This compound typically contributes to the hardening and strengthening of concrete. However, under certain conditions, carbonate ions can also participate in reactions that lead to the formation of expansive compounds, which can potentially damage the concrete structure.

Understanding the specific deterioration mechanisms of these ionic species is crucial for implementing effective corrosion prevention and mitigation strategies in natural draft cooling towers used in petrochemical plants.

2.3 Aggressive Environmental Influence on Concrete Durability

When a concrete component is subjected to a harsh and aggressive environment, it is essential to recognize that the surrounding environmental conditions have the potential to significantly affect its durability. These environmental factors can cause various forms of deterioration, ultimately jeopardizing the concrete's long-term performance. In many instances, the degradation process of concrete involves the penetration and subsequent movement of liquids or gases, which serve as carriers for corrosive agents that penetrate the concrete's pore structure, as explained by Bryant et al. (2009). Therefore, prior to the construction of any reinforced concrete structure, a comprehensive assessment of the environmental factors is imperative.

This assessment should precede the design, concrete mixture formulation, casting, and the commencement of operational activities.

The aggressiveness of the environment in which reinforced concrete structures are constructed plays a key role in determining the durability performance of these structures. In essence, structures subjected to harsh environmental conditions are prone to experiencing premature deterioration, particularly if their durability characteristics are lacking (Ferreira, 2004). This issue becomes particularly evident in the context of petrochemical and power generation plants, where the environmental exposure is notably severe, giving rise to accelerated degradation of reinforced concrete structures. This deterioration can be credited to the presence of detrimental agents that come into contact with the structures.

Considering these challenging exposure environments, it becomes increasingly imperative to allocate greater thought to durability design during the initial phases of a project, as emphasized by Ferreira (2004). Also, for existing structures, it is crucial to develop and implement effective mitigation solutions that explicitly account for the severe exposure conditions as important components of the structure's durability requirements.

Durability design, as a comprehensive approach, encompasses various facets, including service life modelling and prediction. These elements will be subject to investigation as part of this study, allowing for a deeper understanding of concrete structure performance and longevity within the context of demanding environmental conditions.

2.3.1 Characterization and Classification of Exposure Environments

All concrete structures will be exposed to different environments depending on their function and what they required for. Some structures may be subject to environments that are more aggressive than others. The different types of attack for a structure that is exposed to different environments include, structures exposed wastewater or ground water may be subject to sulphate attack, structures in the marine environment are exposed to elevated levels of chlorides, sulphates and magnesium and structures exposed to carbonated waters may subject to leaching or carbonation (Beushausen et al 2021).

Having a comprehensive understanding of the various deterioration mechanisms in concretes due to aggressive agents in a specific environment is crucial for specifying and manufacturing concrete with acceptable performance, and in warranting an acceptable service life and safety performance.

This research focuses on natural draft cooling towers situated within power generation and petrochemical plants, environments are characterized as aggressive due to the emissions released into the atmosphere. The petroleum industry plays a crucial role in providing various domestic products and relies on numerous chemical processes, often involving the combustion of fossil fuels. These chemical processes introduce potential environmental risks, as the combustion of these fuels results in the release of harmful emissions into the atmosphere (Ruland, 2017). These emissions comprise a spectrum of hazards, including air pollution, water pollution, and soil contamination. Petrochemical refineries, serve as sources of air pollutants, including particulate matter, nitrogen oxides, carbon monoxide, hydrogen sulphide, and sulphur dioxide. Furthermore, refineries significantly contribute to the pollution of both ground and surface water. Water within refineries may undergo contamination throughout various stages of the refining process, including desalting, demineralization, and the use of water in cooling towers (Reddy, Ahanger & Gandhi, 2020). It is imperative to acknowledge that while petrochemical refineries in South Africa are subject to regulation and control by a multitude of environmental laws, such as the National Water Act and the Air Quality Act, these laws are primarily intended to enforce mitigating measures, rather than eliminate the release of harsh pollutants. Their goal is to minimize the impact on the surrounding environment to levels deemed acceptable according to relevant legislation.

An integral aspect of this study is to assess the chemical composition of cooling water and determine whether it has a direct or indirect adverse impact on structural durability. Emissions from refinery processes contain harmful agents detrimental to the durability of reinforced concrete (RC) structures, but such effects only manifest when structures come into contact with these aggressive agents.

The operations of oil refineries and petrochemical factories are complex and involve large equipment, often supported by structural steel and reinforced concrete. These structures are exposed to various aggressive process mediums, including hydrocarbons, gases, and corrosive acids. These aggressive mediums are responsible for corrosion in RC structures due to their chemical makeup. Premature steel corrosion in refineries and petrochemical plants is the primary risk factor for structural failure in RC structures (Wu et al., 2013).

Environmental exposure conditions are a critical factor governing the durability of reinforced concrete structures. Engineers must fully understand the range of exposure conditions that structures will be exposed to, to adequately account for durability considerations in the early design stages.

When designing for durability the environment is characterized into an exposure class based on the type of attack from the environment. According to BS EN 206-1:2000 the various exposure classes are dependent on the environment in which the concrete is put into service. An important consideration for a designer to note is that the different exposure classes can act together or individually on any given structure at a given time. This is the case with cooling towers in an environment such as an oil refinery or process plant, where structures are exposed to chloride attack and other aggressive chemical attack. The EN 206-1 exposure classes are divided into six classes as follows and the detail can be found in Table 2.1:

1. No corrosion risk.
2. Chemical attack
3. Carbonation induced corrosion.
4. Chloride induced corrosion from exposure to sea water.
5. Chloride induce corrosion from exposure from other sources besides seawater.

Table 2-1Environmental Exposure Classes : EN 206-1 :2000

Table 1 — Exposure classes

Class designation	Description of the environment	Informative examples where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze/thaw, abrasion or chemical attack For concrete with reinforcement or embedded metal: very dry	 Concrete inside buildings with very low air humidity.
2 Corrosion induced by carbonation		
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 the 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 the 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.
3 Corrosion induced by chlorides other than from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts, from sources other than from sea water, the exposure shall be classified as follows: NOTE Concerning moisture conditions, see also section 2 of this table.		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides.
XD2	Wet, rarely dry	Swimming pools. Concrete exposed to industrial waters containing chlorides.
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides. Pavements. Car park slabs.

Table 1 — Exposure classes *(continued)*

Class designation	Description of the environment	Informative examples where exposure classes may occur
4 Corrosion induced by chlorides from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water, the exposure shall be classified as follows:		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5 Freeze/thaw attack with or without de-icing agents		
Where concrete is exposed to significant attack by freeze/thaw cycles whilst wet, the exposure shall be classified as follows:		
XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents. Concrete surfaces exposed to direct spray containing de-icing agents and freezing. Splash zones of marine structures exposed to freezing.
6 Chemical attack		
Where concrete is exposed to chemical attack from natural soils and ground water as given in Table 2, the exposure shall be classified as given below. The classification of sea water depends on the geographical location, therefore the classification valid in the place of use of the concrete applies. NOTE A special study may be needed to establish the relevant exposure condition where there is: — limits outside of Table 2; — other aggressive chemicals; — chemically polluted ground or water; — high water velocity in combination with the chemicals in Table 2.		
XA1	Slightly aggressive chemical environment according to Table 2	
XA2	Moderately aggressive chemical environment according to Table 2	
XA3	Highly aggressive chemical environment according to Table 2	

2.3.2 Influencing Factors on Durability of Concrete

Concrete durability represents the interface between the concrete system itself and the environment to which it is exposed during its service life. In the area of durability design and evaluation, it is imperative to consider both the characteristic properties of the concrete system and the characteristics of the surrounding exposure environment (Beushausen et al., 2021). The internal properties of concrete encompass its resistance to various forms of degradation, while the external environment dictates the level of severity that the concrete will endure.

Figure 2.3 illustrates a spectrum of factors that exert impact on the durability of concrete. In most durability assessments, the primary determinants typically include the type of binder and the water-to-binder (w/b) ratio, which pertain to the internal attributes of the concrete. Furthermore, considerations related to curing and early-age temperature are important when addressing external characteristics. Notably, one of the most influential environmental factors is the aggressiveness of agents that can potentially deteriorate the concrete. The presence of cracks within the concrete structure can further worsen environmental related degradation, as these cracks may enable the ingress of harmful substances into the concrete matrix (Beushausen et al., 2021).

As emphasized, the process of designing concrete for durability should commence at the conceptual stage of a project. This approach necessitates a holistic approach that encompasses structural considerations, service life modelling, predictions of deterioration, the implementation of adequate construction quality systems and procedures, and careful material design. Each of these facets plays an important role in ensuring the long-term durability and performance of reinforced concrete structures.

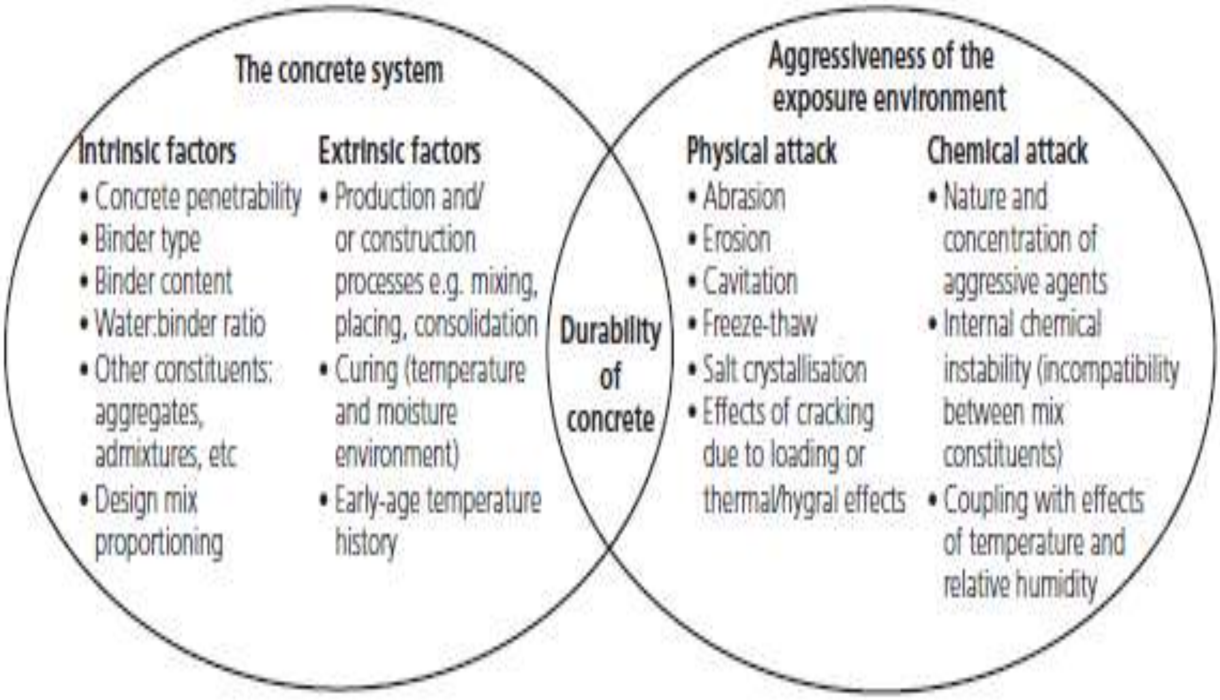

Figure 2-3: Factors Influencing the Durability of Concrete (Beushausen et al, 2021)

2.4 Transport Mechanisms

The rate at which deterioration occurs in concrete structures is frequently dependent upon the transport of harmful elements into the concrete matrix. Therefore, it becomes imperative to comprehend the underlying transport mechanisms within concrete, as these mechanisms play a pivotal role in determining its durability. Various degradation processes, including carbonation, the infiltration of chlorides, or sulphate attacks, are all intimately linked to the concrete's ability to facilitate the penetration of fluids or ions through its microstructure (Beushausen et al., 2021).

The ingress of aggressive chemicals or substances is subject to various transport mechanisms within the concrete medium. These transport mechanisms are reliant upon the penetrability of the concrete, which can be defined as the extent to which the concrete enables the movement of gases, liquids, or ions through its pore structure. In essence, penetrability is a measure of how easily aggressive substances can infiltrate the concrete. The penetrability of concrete is characteristically reliant on the pore structure and the interconnectivity of these pores within the concrete matrix. These factors collectively dictate the concrete's susceptibility to the ingress of harmful agents and, subsequently, its durability.

The different transport mechanisms"are 'orption, permeation, migration, diffusion and convection. It is important to note that multiple transport mechanisms may operate concurrently, although typically one mechanism dominates. These mechanisms are characterized by the driving forces that drive the transportation of harmful agents. The transport properties of concrete are of critical significance in determining its durability, and these properties are dependent on the concrete's condition. Once concrete becomes cracked or exhibits defects, the transport mechanisms move their path, bypassing the intact concrete and traveling through the cracks or defects. In the context of cracked concrete, permeability is influenced by crack properties, whereas in uncracked concrete, it is correlated with concrete porosity. This research will consider the properties of transport mechanisms in both cracked and uncracked concrete.

In the context of cracked concrete, transport mechanisms take on a unique significance. Cracks in concrete basically change the pathways through which fluids and ions migrate within the material. Permeability in cracked concrete becomes fundamentally linked to the characteristics of these cracks. The width, length, and distribution of cracks directly influence the rate at which aggressive substances can penetrate the concrete matrix. In principle, cracks serve as pathways for the accelerated transport of detrimental agents, allowing them to bypass the intact concrete and reach the embedded steel reinforcement. As a result, understanding and quantifying the impact of cracks on transport mechanisms is imperative in assessing the durability and corrosion susceptibility of reinforced concrete structures (Beushausen et al., 2021).

In most cases, RC structures experience corrosive actions when detrimental elements penetrate the surface zone of the concrete, referred to as the concrete cover (Kropp & Alexander, 2007). These corrosive actions include:

1. Corrosion of Steel Reinforcement due to Chloride Ingress: The ingress of chlorides damages the passivated film layer of the steel, leading to the depassivation of steel. The rate of chloride ingress dictates the time until corrosion initiation.
2. Corrosion of Steel due to Carbon Dioxide Ingress: CO_2 ingress reduces the alkalinity of the concrete, subsequently damaging the protective film layer on the steel.

The transport mechanisms related to these corrosive actions are elaborated upon in more detail below. It is important to note that this research will not include numerical modeling of each transport mechanism, but rather focus on available tests to assess the impact of these mechanisms.

Transport properties of concrete hold an essential role in determining durability, as various deterioration mechanisms, such as carbonation, chloride ingress, or sulphate attack, are linked to the ease with which fluids or ions can permeate the concrete's microstructure.

2.4.1 Permeation

Permeation within concrete involves both gas and water permeation processes. Permeation, as defined in the context of saturated concrete, signifies the capacity of concrete to permit the flow of liquids and gases through its interconnected pore structure, a phenomenon achievable only under applied pressure conditions (Kropp et al., 2007).

This flow caused by applied pressure is also commonly referred to as advection (Claisse, 2014). Advection sets itself apart from permeation by the requirement of external pressure to initiate fluid flow through the concrete. The quantification of fluid or gas movement through concrete is typically achieved through the application of Darcy's Law and is expressed as follows (Otieno et al 2008):

$$v = (\frac{k}{n})(-\frac{dh}{dx}) \quad (2.1)$$

where:

k = permeability coefficient

n = porosity

h = hydraulic head

x = distance

2.4.2 Sorption

Capillary forces serve as the dominant driving mechanism behind sorption processes in concrete. These forces compel liquids to infiltrate the pore structure of unsaturated or partially saturated concrete. Capillary suction, a critical aspect of this mechanism, arises from the tension-driven surface interactions between the porous material and the penetrating fluid. Sorption exhibits a strong correlation with the pore structure of the concrete, as it is primarily influenced by the dimensions of the capillaries within the material. The ingress of water into concrete is closely linked to the size of these capillaries. Smaller capillaries exhibit higher capillary pressure due to their reduced surface area, consequently enhancing capillary action by reducing the intermolecular forces of the liquid. Conversely, larger capillaries exhibit lower capillary pressure, resulting in decreased capillary action. This relationship between capillary size and sorption behaviour plays a decisive role in the moisture ingress characteristics of concrete, as illustrated in Figure 2.4 (Claisse, 2014). Sorptivity, the measure of movement of a liquid through a dry or semi saturated material can be expressed as (Otieno et al 2008):

$$S = \frac{\Delta M}{t^{\frac{1}{2}}}\left(\frac{d}{M_{sat}-M_0}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}$$

where:

$\frac{\Delta M}{t^{\frac{1}{2}}}$= slope of the straight line produced when the mass of water absorbed is plotted against the square root of time

d = sample thickness

M_o & M_{sat} = saturated mass and dry mass of concrete respectively

Understanding these dynamics is essential for understanding and managing moisture-related issues in concrete and optimizing its durability and long-term performance.

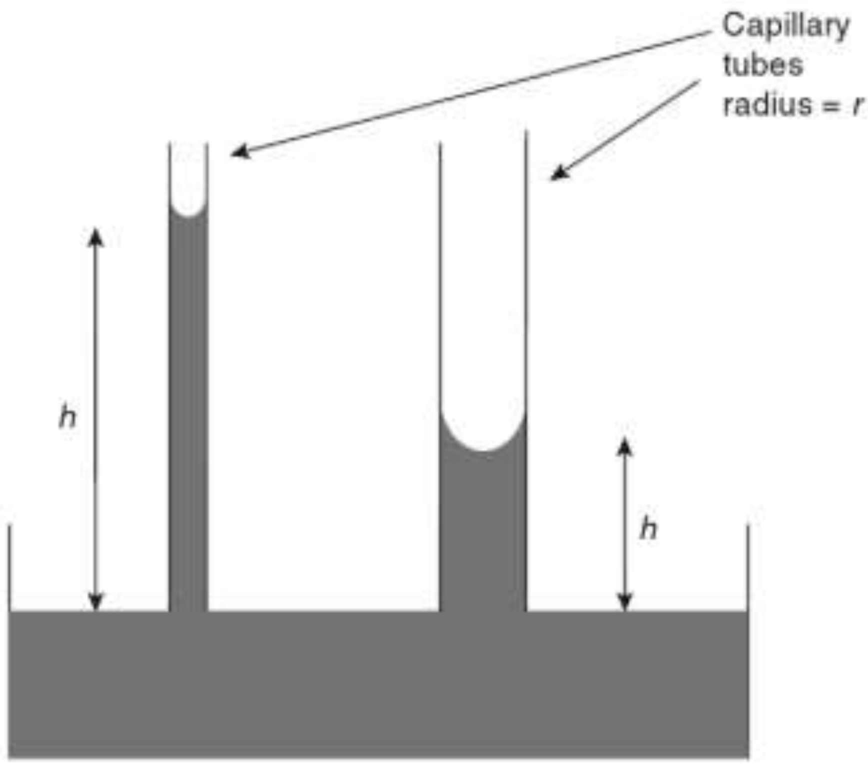

Figure 2-4: Capillary Rise versus Capillary Diameters (Claisse, 2014)

2.4.3 Diffusion

Diffusion represents a pivotal transport mechanism governing the movement of chloride ions (Cl-) and carbon dioxide (CO2) through concrete, critically influencing its durability. Diffusion, in essence, refers to the flow of ions, gases, and molecules from regions of high concentration to those of lower concentration within the concrete matrix. This molecular, gaseous, and ionic movement manifests under various concrete conditions. Molecular diffusion, for instance, occurs through the interconnected large pores and pore structure of the concrete, facilitating the movement of molecules. Gaseous diffusion, on the other hand, transpires in non-saturated concrete conditions, while ionic diffusion can transpire both in fully and partially saturated concrete.

The process of diffusion is described and modelled using Fick's 1st and 2nd Laws of diffusion. The 1st law pertains to steady-state diffusion, while the 2nd law is applicable to non-steady-state diffusion. Fick's Law articulates the movement of particles as they migrate from regions of higher concentration to those of lower concentration. In other words, the greater the difference in concentration between two points, the higher the rate of diffusion, as explained by Thompson (2006). Fick's first law of diffusion can be used to express the rate of diffusion of a gas into a permeable material (Otieno et al 2008):

$$J = -D_{eff}\frac{dC}{dx} \quad (2.3)$$

where:

J = mass transport rate (g/m^2s)

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

dC/dx = concentration gradient (g/m^4)

C = Concentration of fluid (ion or gas)

x = distance (m)

Understanding and using these diffusion principles is essential to understanding and predicting the transport of substances within concrete, which is essential for assessing its durability and resistance to environmental factors such as chloride ingress and carbonation.

2.4.4 Migration

Migration is similar to diffusion in the sense that it is a mechanism that allows for the movement of ions. The difference here, it is done under the influence of an electrical potential difference. The source of the potential difference may be internal or from an external source. The electrochemical process required for corrosion of the reinforcing steel can provide the potential difference required to initiate migration. (Claisse, 2014).

Migration, a critical transport mechanism within concrete, revolves around the electromigration of charged ions through the porous microstructure of the material under the influence of an applied electric field (Song, 2017). This mechanism holds implications for the durability and serviceability of concrete structures, particularly in the context of chloride-induced corrosion of embedded steel reinforcement (Angst, Elsener, Larsen & Vennesland 2016).

In concrete, charged ions, such as chloride ions (Cl-), can migrate within the aqueous phase of the material when subjected to an external electric field. This migration phenomenon can significantly increase the rate of ingress of harmful ions toward the embedded steel, thereby increasing the risk of corrosion (Monteiro & Kurtis, 2013). The rate of ion migration is linked to various of factors, including the magnitude of the applied electric field, the concentration of ions in the pore solution, the pore structure and connectivity within the concrete, and the electrical resistivity of the material (Gong. Zhao, Chen B & Chen X, 2015). Migration is described using the Nernst-Planck equation (Otieno et al 2008):

$$v = (D\frac{zF}{RT})(\frac{dU}{dx}) \ldots\ldots\ldots\ldots \text{(2.4)}$$

where:

v = velocity of the ionic species

D = diffusion coefficient of the ionic species

z = electrical charge (ionic valence)

F = Faraday"s constant

T = absolute temperature

U = potential difference across the sample

x = distance variable

R = universal gas constant (8.314 J/molK)

Understanding and effectively managing ion migration in concrete are paramount for evaluating material durability, predicting the risk of reinforcement steel corrosion, and formulating protective measures to enhance the service life of concrete structures exposed to aggressive environmental conditions (Tang, Wang & Zhao., 2018).

2.4.5 Convection

Convection entails the bulk movement of liquids or gases through the porous microstructure of the material driven by fluid pressure gradients. This mechanism plays a role in various concrete-related processes, particularly in the context of moisture transport and its implications for durability and service life.

In concrete, convection as a transport mechanism is typically observed in scenarios where the material is subjected to external factors such as hydraulic pressure, temperature gradients, or fluid flow. One example is the transport of water through concrete under the influence of hydraulic pressure, such as in underground structures or structures exposed to hydrostatic loads (Houst & Wittmann, 2013). Convection can also occur during temperature differentials within the concrete, where thermal convection causes the movement of water or other fluids (Lupo & Cusatis, 2014).

Convection is the movement of a chemical solution through the concrete. The driving force in this transport mechanism is the bulk movement of a body of water through the concrete. The surface of the concrete face is most prone to wetting and the subsequent drying action. (Kellerman et al 2009). Convection can be expressed as (Otieno et al 2008):

$$\frac{\partial C}{\partial t} = -v\frac{-\partial^2 C}{\partial x^2} \quad \text{.............................. (2.5)}$$

where:

C = Concentration of solute at depth x after time t

v = average velocity vector of fluid flow

During this wetting, depending on the exposure environment of the concrete, the water may transport chlorides or other aggressive elements in the water. Natural draft cooling towers in a petrochemical or power generation plant are prime examples of a structure exposed to wetting and drying cycles. Through the mass movement of water, the chlorides ingress into and out of the concrete through convection at the surface. The convection zone of the concrete occurs at the surface and extends to a depth where diffusion becomes the significant mechanism. This is depicted in Figure 2.5.

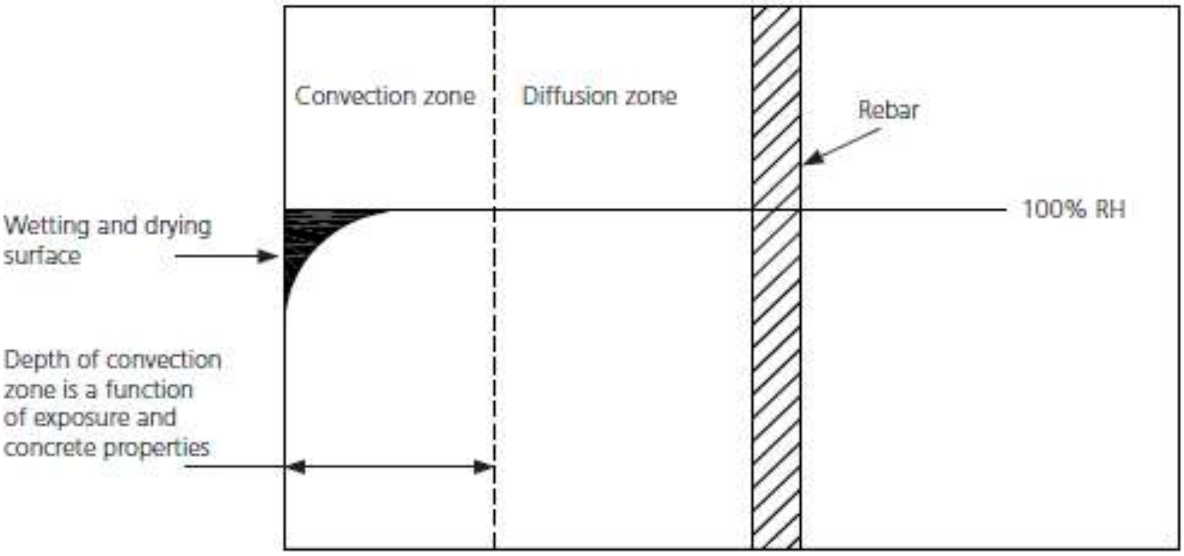

Figure 2-5: Convection Zone in Concrete (Beushausen et al, 2021)

2.4.6 Aged Structures

Transport mechanisms in aged concrete structures are of paramount importance for understanding and assessing the durability and long-term performance of these structures. As concrete ages, it undergoes complex physical and chemical changes that can significantly impact its transport properties, including diffusion, sorption, and convection processes (Monteiro, Miller & Horvath., 2012). These transport mechanisms play a critical role in the ingress of aggressive agents, such as chlorides and sulphates, which can lead to the deterioration of concrete over time.

Diffusion, a fundamental transport mechanism, continues to influence the movement of ions and gases within aged concrete (Xie, Wang, Xie & Cheng, 2020). Sorption, on the other hand, may evolve due to alterations in the concrete's pore structure and porosity because of aging (Yu, Li, Liu, Shi & Ou, 2016). Convection mechanisms, driven by hydraulic pressure or temperature differentials, may also change with the aging of concrete structures (Alonso, Andrade & Castelotte, 2014).

Understanding these evolving transport mechanisms is crucial for predicting the durability and service life of aged concrete structures. It involves the application of advanced modelling techniques, experimental investigations, and field assessments to adapt maintenance and rehabilitation strategies to the changing transport characteristics of aging concrete.

The manner in which transport mechanism behave changes during the life of a structure. The reason for this is due to the continuous hydration process of the concrete but also the deterioration of a structure. The deterioration of a concrete structure may affect the penetrability of the concrete element. This results in harsh elements present in the environment to penetrate the structure more easily (Beushausen et al 2021).

2.5 The Durability Index (DI)

The durability index (DI) tests developed in South Africa provide measures of the resistance to penetrability of cover concrete (Nganga, Beuhausen and Alexander, 2017). Within the context of South Africa, durability indices (DIs) have been used as test methods linked with transport mechanisms such as gaseous and ionic diffusion and water absorption (Beushausen et al. 2021). These DIs serve as indicators of the material's ability to withstand external environmental forces. They are derived from three fundamental test methods:

1. **Chloride Conductivity Index Test (CCI):** This test assesses the concrete's resistance to the ingress of chloride ions, which are often an indication of structural deterioration.
2. **Oxygen Permeability Index Test (OPI):** This method gauges the concrete's capacity to resist the permeation of gases, particularly carbon dioxide, which can lead to corrosion and degradation.
3. **Water Sorptivity Index Test (WSI):** This test evaluates the concrete's resistance against the penetration of liquids, which can trigger various forms of damage.

The results obtained from these DI tests are not only valuable but also serve as essential inputs for the development of service life prediction (SLP) models. These predictive models facilitate the estimation of a structure's projected service life based on an analysis of various factors, including environmental exposure conditions, cover thickness, and concrete quality. The three test methods are employed to ensure the long-term performance of reinforced concrete (RC) structures, with each test serving a specific purpose. The OPI plays a crucial role in the Carbonation Service Life Prediction (SLP) model, while the Chloride Conductivity Index is instrumental in characterizing material quality, especially concerning chloride-induced corrosion.

The three tests measure different transport mechanisms in concrete to investigate its potential durability performance. The tests however, regardless of the critical indications they provide regarding durability performance of a structure in a particular exposure environment, the tests were developed to be used on new structures and not necessarily accurately predict the performance of existing structures that have been in service for more than 40 years as is the case with the Secunda Cooling Towers, which is the focus of this study. These tests have proven to be a powerful tool in performance-based durability design (Otieno et al 2008).

The three durability index tests were developed and proved in the laboratory. The tests, however, haven't been performed on concrete of existing structures under normal site conditions. (Gouws., Alexander, and Maritz, 2001). An investigation conducted by Gouws et al was considered necessary to determine if it would be possible to use the durability index tests to determine the quality of site concrete. If the tests provide consistent results, a basis would be created for producing specifications that would ensure durability more directly, using permissible index values for concrete elements, Alexander (1997).

Durability index testing of concrete structures should ultimately relate to the durability performance of structures in service. There are various reasons for preferring a more analytical laboratory approach. These include in-situ concrete being exposed to several influences (i.e., environmental exposure) that are difficult to quantify, design and construction data is sometimes unreliable, and assessing durability performance is relatively subjective as stated by (Stroheimer and Alexander, 1996).

Despite these practical limitations useful information can be obtained about the long-term behaviour of concrete under real in-service conditions. This information is essential for confirming trends established from early-age laboratory and field exposure studies.

Durability Index (DI) tests conducted on mature concrete structures can offer valuable insights into their long-term durability performance potential. These tests assess key transport properties (e.g., oxygen permeability, chloride conductivity) that directly influence concrete deterioration mechanisms. The resulting data can inform:

- **Future design parameters:** Optimized concrete mixes and construction methods based on in-situ as built performance feedback.
- **Construction specifications:** Targeted improvements to ensure long-term concrete durability.

- **Inform Repair strategies:** Data-driven decisions for effective remedial actions based on concrete quality assessment.

Lampacher (2000) proposed a framework for evaluating the long-term performance of mature concrete structures by integrating early-age durability index tests with periodic direct performance monitoring. By comparing early-age DI results with subsequent measurements and direct performance data, a comprehensive understanding of the concrete's performance trajectory throughout its service life can be achieved.

By implementing Lampacher's (2000) recommended approach, valuable insights can be gained to guide design, construction, and repair strategies, ensuring the long-term durability performance and sustainability of concrete infrastructure.

2.6 Durability Design Considerations

Designing for durability in reinforced concrete (RC) structures within aggressive environments is focused on concrete's ability to withstand the penetration of harmful substances throughout its projected operational design life. The determining factor in ensuring resistance against these aggressive agents predominantly focuses on the quality and thickness of the protective cover concrete layer protecting the reinforcement steel. The cover layer is significant because it is the initial line of protection against the intrusion of harmful substances into the concrete matrix (Beushausen et al. 2021). The effectiveness of this cover layer is reliant upon the careful adherence to high quality construction practices. Poor construction practices, such as insufficient curing and inadequate compaction, can result in the formation of a cover layer that is highly susceptible to penetration by harmful external agents.

Environmental classifications utilized in these models are linked to the EN 206-1 classes. Furthermore, the quality of the concrete is represented by the relevant DI parameters, signifying the integral role these indices play in accurately predicting the lifespan and durability of reinforced concrete structures in aggressive environments.

SLP models, such as the Carbonation SLP model, are valuable in both the design and performance specification of new structures. They allow for the selection of appropriate concrete quality (typically represented by the Durability Index, DI value) and cover thickness for specific binders. The objective is to ensure that the selected concrete can withstand the corrosive impact of various aggressive agents. This integrated approach, linking material properties to the expected service life of RC structures within their environmental context, aligns with the principles outlined in the Fédération Internationale du Béton (FIB) model code for service life design (Muigai., Moyo, and Alexander, 2012).

It is fundamental to recognize that many failures in concrete structures can be due to insufficient durability as a result from inadequate design and execution. Existing building codes establish exposure classifications and associated requirements primarily through "deemed-to-satisfy" boundaries, ultimately addressing durability concerns. Durability performance tests are rarely specified, typically being project specific. Compliance with code requirements does not guarantee the durability of structures in severe exposures. Durability design must incorporate a broader scale, including the mitigation of cracking and the provision of adequate curing. The development of standards for durability in both design and construction, guided by durability experts, becomes imperative (Hooton, 2019).

Concrete exposed to severe environmental exposure conditions, it is vital to formulate codes and specifications that are more detailed, addressing both durability design and the construction of durable concrete. An example relating to minimum curing requirements is often based on achieving a small percentage of the specified strength. This will now need to be revised to ensure resistance to fluid penetration within the cover layer that is protecting reinforcing steel, is also considered. The adoption of performance-based test methods that directly correlate with durability is crucial. However, it is acknowledged that new and improved test methods are warranted, as existing ones do not fully encompass all potential deterioration mechanisms or align seamlessly with field performance (Hooton, 2019).

Internationally, various codes such as the United States and Canadian standards (ACI and CSA), European codes and standards (EN 206) as well as the Chinese durability standards (Chinese GB/T 50476) share common elements, including the definition of exposure classes and the provision of "deemed-to-satisfy" requirements for concrete (Hooton, 2019). These requirements ultimately address durability by specifying minimum strengths, maximum water-cement or water-cementitious materials ratios, and minimum cement contents for specific aggressive exposures. However, compliance with these requirements does not guarantee equal levels of durability among different concretes. For example, concretes constructed with blended cements or supplementary cementitious materials and subjected to proper placement and curing exhibit significantly lower rates of permeability and chloride ingress compared to concretes using plain Portland cement at the same water-binder ratio.

Despite their structural design quality, current codes often fail in specifying requirements for durability design and achieving durability in construction (Hooton, 2019). To address durability effectively, this would require expertise from experts in the durability and materials science industries, leading to collaborations between durability consultants and structural design consultancies. In this regard, the fib Model Code 2010 and the Concrete Institute of Australia's Concrete Durability Series of Standard Practices serve as examples, offering different approaches for dealing with various environmental exposures, including freezing and thawing, chloride ingress, and carbonation. Inspired by these alternate methodologies, the American Concrete Institute's (ACI) Durability Committee has recently initiated the development of durability specifications (Hooton, 2019).

2.6.1.1 Prescriptive vs Performance-based Design

"Traditional durability design approaches are based on prescribed limiting values for selected mix design and concrete parameters such as w:b ratio, compressive strength and cement content" (Beushausen et al 2021).

The prescriptive values for the mentioned parameters are defined in accordance with the exposure class of the environment. EN 206 (BS EN 206 2013) describes four exposure classes for concrete exposed to. One class for the effect of carbonation and three classes for concrete that is exposed to marine environments. The specifications generally specify minimum cover depths based on the exposure environment classes, with values that range from a minimum of 30 mm to 50 mm when corrosion of reinforcing steel is a major problem. These values are based on a design service life of 50 years. For a service life of 100 years, the minimum cover concrete depth is increased, by about 10 mm. Cover depth may also be reduced provided corrosion mitigation techniques are used such as the use of migrating corrosion inhibitors, protective coatings and other mitigation techniques. Prescriptive design approaches are now being scrutinized more and more for failing to sufficiently define the concrete' s resistance against the mechanisms of deterioration in particular carbonation and chloride induced corrosion. (Beushausen et al, 2021). In addition, prescriptive approaches to design also do not account for service life requirements. Prescriptive approaches also allow room for over design of structures thus resulting in un-economical concrete structures.

An appropriate design method to durability of reinforced concrete structures is a method that is based on the evaluation of the concrete's materials' performance. A performance-based approach is based on the measurement of the associated material properties that can result in the deterioration of concrete in a specific exposure environment. If the measurements are done on existing structures, the results would allow for the quantification of the influence exposure environments, material make-up and on-site quality control during construction have on the structure. Having the aforementioned in place, durability performance and service life prediction of a structure becomes possible.

The two approaches are discussed below:

Performance based design approach

The performance-based "deemed-to-satisfy" approach offers a more standardized basis, relying on results from SLP models. The nature of the "deemed-to-satisfy" approach has its limitations. Adaptability in the models' considerations introduces uncertainties into the prediction of RC structure deterioration, requiring a probabilistic tool to account for these factors. Such a probabilistic SLP model would offer a variety of expected times for corrosion to initiate, providing asset owners with a more balanced and accurate basis for selecting durability parameters and making economically sound decisions regarding RC structures. This approach promotes an equilibrium between economic considerations and structural safety (Muigai, R., Moyo, P., and Alexander, M., 2012)

This approach defines the acceptable durability performance criteria, methods of testing and conformance for a given minimum service life and exposure environment for a reinforced concrete structure. This approach avoids the prescriptive way in which criteria will be specified. This approach allows for greater flexibility and innovation in achieving the specified or required durability performance through the evaluation and implementation of the most cost-effective methods (Demis, 2019). This approach involves laboratory testing in defining the performance and quality criteria as per the durability indices which will discussed in chapter 3.

An advantage of the performance-based design approach is that the quality from a concrete perspective, of the as-built structure can be measured and necessary actions taken if the minimum standards for durability are not met (Beushausen et al 2021).

Prescriptive design approach (Deemed to satisfy approach)

The prescriptive approach defines the requirements for material composition and construction specifications for the exposure environment that the structure will be put into service, the required service life and durability performance of the structure. This approach can be stated to be a cook-book approach to design where there are limits that are imposed on specific concrete parameters such as minimum compressive strength, minimum and maximum water/biner (w/b) ratio, in order to achieve a certain degree of durability performance for a specific exposure environment (Ballim, Alexander & Beushausen, 2009).

Performance approaches can be applied in different stages of a project that related to design, construction specifications, quality requirements and implementation. (Beushausen et al 2021).

2.6.2 Service Life Modeling

The estimation of the service life of a concrete structure is a critical aspect of structural engineering, involving the use of quantitative service life models to predict the duration before severe damage occurs within a specific exposure environment (Beushausen et al., 2021). Data collected both on-site and in controlled laboratory settings play a crucial role in the development of these service life models. In scenarios involving the infiltration of chloride ions or carbon dioxide (CO_2) into a structure, determining the rate of ingress allows for the assessment of the time until corrosion initiation is likely to occur. As a result, this modelling approach enables the anticipation of the degradation propagation in a reinforced concrete (RC) structure, thereby enabling the implementation of successful maintenance strategies.

Service life models tailored for RC structures vulnerable to corrosion aim to forecast the pace at which contaminants penetrate the concrete, leading to steel corrosion (Alexander & Beushausen, 2019). The service life of such structures concerning steel reinforcement corrosion is typically divided into two distinctive phases: initiation and propagation, as illustrated in Figure 2.6.

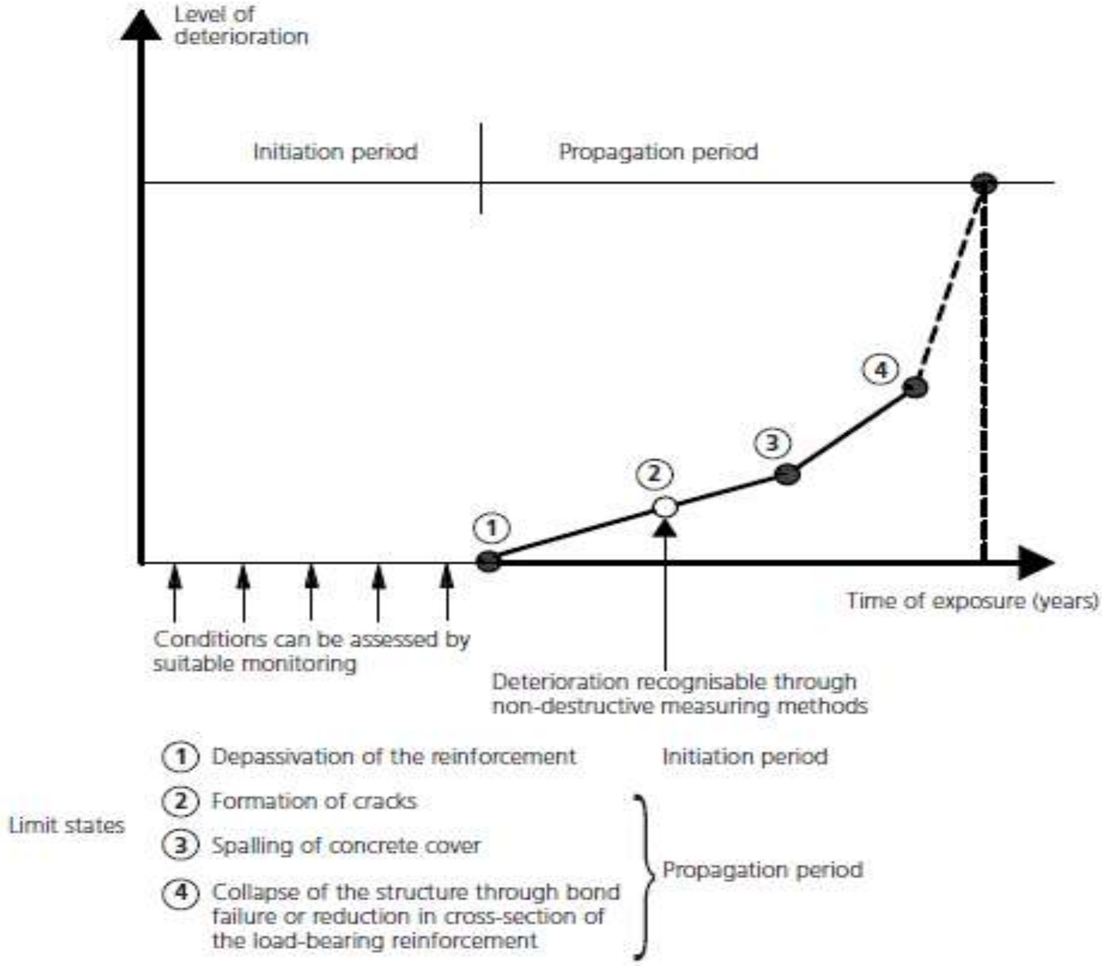

Figure 2-6: Two Stage Service Life Model (Beushausen et al, 2021)

The duration of the initiation phase is dependent on various factors that include the environmental conditions to which the structure is exposed and the thickness of the concrete cover protecting the steel reinforcement. Additionally, the concrete's permeability and the rate of ingress of aggressive elements has significant influence over the initiation phase of corrosion. Naturally, corrosion initiation is triggered by factors such as the neutralization of the concrete's pH or the high concentration of chlorides within the pore solution surrounding the reinforcing steel. It is crucial to note that corrosion of the reinforcing steel only commences once external agents have breached the concrete cover and come into contact with the reinforcement steel. The period taken for these external elements to reach the reinforcement steel is referred to as the initiation period (Tuutti, 1982). During this phase of the corrosion model, no visible damage is typically observed.

Conversely, the propagation phase of the corrosion model marks the onset of steel corrosion, potentially impacting the serviceability of the RC structure. Once the depassivation of the protective layer around the reinforcing steel occurs, corrosion takes place in the presence of moisture and oxygen. The rate of corrosion is influenced by various factors, with temperature and humidity levels being particularly influential. Throughout the propagation phase of corrosion, the concrete undergoes a series of stages, as illustrated in Figure 2.2. These stages are often referred to as undesirable events in the service life of concrete. Corrosion can manifest either uniformly along the length of the reinforcing steel or at localized points. For instance, carbonation-induced corrosion exemplifies uniform corrosion, also known as Microcell corrosion, while chloride-induced corrosion is an instance of localized corrosion, or Macrocell corrosion (Bertolini, Elsener, Pedeferri, Redaelli & Polder, 2013).

2.7 Mechanisms of Deterioration in Reinforced Concrete Structures

The degradation of concrete, especially reinforced concrete, holds significant consequences for the sustainability, safety, and long-term viability of civil infrastructure, particularly in challenging environmental conditions (Ferreira, 2004). This research aims to explore into the causing mechanisms of deterioration within reinforced concrete structures, specifically Natural Draft Cooling Towers. The harsh operating conditions characteristic of power generation and petrochemical plants can substantially impact the performance and durability of these cooling towers.

Reinforced concrete has long been favoured for its durability in construction. However, concrete possesses characteristic limitations influenced by material properties, design considerations, construction methodologies, quality assurance practices, and exposure to harsh environmental conditions, all of which can accelerate its deterioration. Various factors contribute to concrete deterioration, and this study will explore these mechanisms in detail.

Concrete deterioration mechanisms, such as alkali-aggregate reactions, freeze-thaw cycling, and the corrosion of embedded steel, deserve thorough investigation and consideration in the interest of concrete durability. Among these deterioration mechanisms, the most prevalent in reinforced concrete structures is the corrosion of reinforcing steel, primarily through processes like carbonation and chloride-induced corrosion. Through site investigations, condition assessments, and comprehensive reviews of existing literature, this study seeks to ascertain the primary deterioration mechanism affecting cooling towers.

It Is necessary to understand all mechanisms related to concrete deterioration and how they collectively impact the integrity of reinforced concrete structures. These mechanisms may occur individually or interact in combination.

Environmental factors, including temperature variations, moisture exposure, air contaminants, solar radiation, and wind, play a decisive role in the degradation of materials used in the outer envelope of structures (Ferreira, 2004). In the case of cooling towers, these environmental factors significantly affect the exterior shell. Furthermore, these environmental influences fluctuate across different locations and seasons. During its service life, the relationship between deterioration mechanisms can either increase the rate of degradation or, albeit less often, reduce the rate of deterioration by working against one another.

Concrete deterioration can manifest through various physical or chemical mechanisms. The deterioration processes result from the complex interaction between the concrete itself and its environmental exposure. The likelihood and rate of a specific deterioration form are dependent upon the aggressiveness of the exposure environment and the concrete's physical and chemical resistance (Beushausen et al., 2021).

Regarding concrete deterioration, several general statements and mitigation measures can be delineated. As per Beushausen et al., these can be summarized as follows:

- For most deterioration mechanisms, the rate of deterioration may be reduced by the use of a good quality concrete. This is of particular importance in the cover concrete zone of the structure.
- The movement of aggressive agents through the pore structure of a concrete matrix promotes deterioration of concrete. The transport mechanisms of the concrete are important factors in controlling the rate of deterioration the concrete structure.
- Concrete that is in service in a dry environment will deteriorate at a slower rate than a concrete that is in service in a wetter or humid environment. The extent of deterioration is also significantly reduced if the concrete is cast in a drier environment. This also reduces the chances of the concrete deterioration to initiate.
- The addition of supplementary cementitious materials to concrete may enhance the durability parameters of the concrete as they influence the concrete resistance to deterioration.

2.7.1 Physical Deterioration Mechanisms

2.7.1.1 Abrasion and Erosion

Abrasion and erosion are prominent deterioration mechanisms in concrete structures, primarily driven by mechanical wear and the physical forces exerted by abrasive materials and erosive agents. These mechanisms hold significant importance in understanding and assessing the durability and long-term performance of concrete in various applications.

Abrasion is form of attack on concrete that can be defined as damage that occurs when the concrete surface has limited ability to resist wear caused by rubbing or friction. In general, the concrete's hardness, which is related to its surface hardness and compressive strength determines how strong it will be to resist abrasion" (Yazici et al.,2007). During the process of wear, the external paste of the concrete wears away and exposes the aggregates. This abrasive action can lead to the removal of surface layers and the exposure of underlying concrete, ultimately resulting in surface degradation (Ghani & Azmi, 2018). Upon exposure, concrete becomes susceptible to additional deterioration due to the forces of impact and abrasion. While wind-borne particles have the potential to induce abrasive effects, the most prevalent and severe instances of abrasion typically arise in environments characterized by vehicular traffic on concrete surfaces and within hydraulic structures subject to flowing water.

Compressive strength plays a pivotal role in dictating the abrasion resistance of concrete, with greater compressive strength correlating with heightened resistance to abrasion. In instances where concrete, such as warehouse floors exposed to abrasive forces, requires an extended service life, the incorporation of harder aggregates can substantially enhance durability (Portland Cement Association, 2002).

Erosion, as explained in Fulton's Concrete Technology, can be characterized as a specialized indication of abrasion. This form of abrasion develops from the wearing action of fluids, suspended solids, and wind-borne particles, leading to the gradual wear of concrete surfaces (Ballim et al., 2009).

2.7.1.2 Freeze-thaw

Freeze-thaw deterioration is a deterioration mechanism that can significantly impact the durability of concrete structures, particularly in regions subject to freeze-thaw cycles. This mechanism is characterized by the repeated freezing and thawing of water within the concrete matrix, leading to a cycle of expansion and contraction.

When water within the concrete freezes, it undergoes a volumetric expansion of approximately 9%, exerting substantial pressure on the pore structure of the concrete. If this expansion exceeds the tensile strength of the concrete, it can result in the formation of voids and cracks, ultimately compromising the structural integrity of the material (Ballim et al., 2009).

The detrimental effects of freeze-thaw cycles are aggravated in environments with fluctuating temperatures, where water repeatedly freezes and thaws. These temperature induced expansions and contractions can lead to the increasing deterioration of concrete, with visible signs such as surface scaling, spalling, and cracking.

While freeze-thaw deterioration is a significant concern in regions with cold climates, it may also be relevant in certain specialized environments where temperature variations can expose concrete structures to this mechanism. Therefore, understanding and mitigating the effects of freeze-thaw cycles are essential aspects of concrete durability design and maintenance.

2.7.1.3 Salt Crystallization

Surface scaling of concrete, caused by salt crystallization, characterizes a well-known and consequential form of concrete deterioration. Despite its recognition, there exists a lack of agreement regarding the mechanism governing this form of degradation. Researchers have proposed various mechanisms, which can be broadly categorized into three primary groups (Thaulow & Sahu, 2004):

i) Solid Volume Change during Transformation: This mechanism suggests that the deterioration of concrete occurs due to the solid volume change experienced during the transformation of anhydrous salts to their hydrous form. When salts absorb water from the concrete matrix, they undergo a volumetric expansion, leading to the development of internal stresses that contribute to surface scaling.

ii) Salt Hydration Pressure: This mechanism is related to the degradation that is related to the pressure generated by the hydration of salt crystals within the concrete structure. As salts hydrate, they expand, exerting expansive forces on the surrounding concrete. This pressure accumulation contributes to surface scaling and deterioration.

iii) Salt Crystallization Pressure: This mechanism suggests that the cause of concrete deterioration is the pressure exerted by the crystallization of salts within the concrete's pore structure. When dissolved salts within the concrete matrix crystallize, they occupy a larger volume, resulting in the development of expansive forces that can damage the concrete surface.

As part of this research, a detailed investigation into these proposed mechanisms will be studied, aiming to shed light on the factors governing surface scaling due to salt crystallization. Furthermore, the study will examine the relevance and applicability of these mechanisms in the context of cooling towers within petrochemical and power generation plants, where exposure to harsh environmental conditions is a common circumstance.

By studying the details of these mechanisms and their role in concrete deterioration, this study seeks to contribute valuable understandings that can guide effective mitigation strategies and enhance the durability performance of concrete structures in such specialized environments.

2.7.2 Chemical Deterioration Mechanisms

Chemical deterioration mechanisms in concrete refer to the processes by which various chemical reactions and environmental factors can reduce the structural integrity and durability of concrete. These mechanisms can significantly impact the long-term performance of concrete structures.

In concrete material science, it is important to understand that concrete possesses a characteristic pore solution pH level ranging between 12 and 13, allowing it to be susceptible to chemical disequilibrium with its surroundings. This fundamental chemical makeup of concrete stands as a fundamental factor in its capacity to withstand adverse environmental conditions. Environments that are characterized by significant chemical aggressiveness, demonstrated by petrochemical facilities or power generation plants, are acknowledged as tough challenges for concrete structures due to their potential to induce harmful effects, as explained by Beushausen et al 2021.

Figure 2.7 below depicts the different categories of the mechanisms of deterioration related to chemical attack.

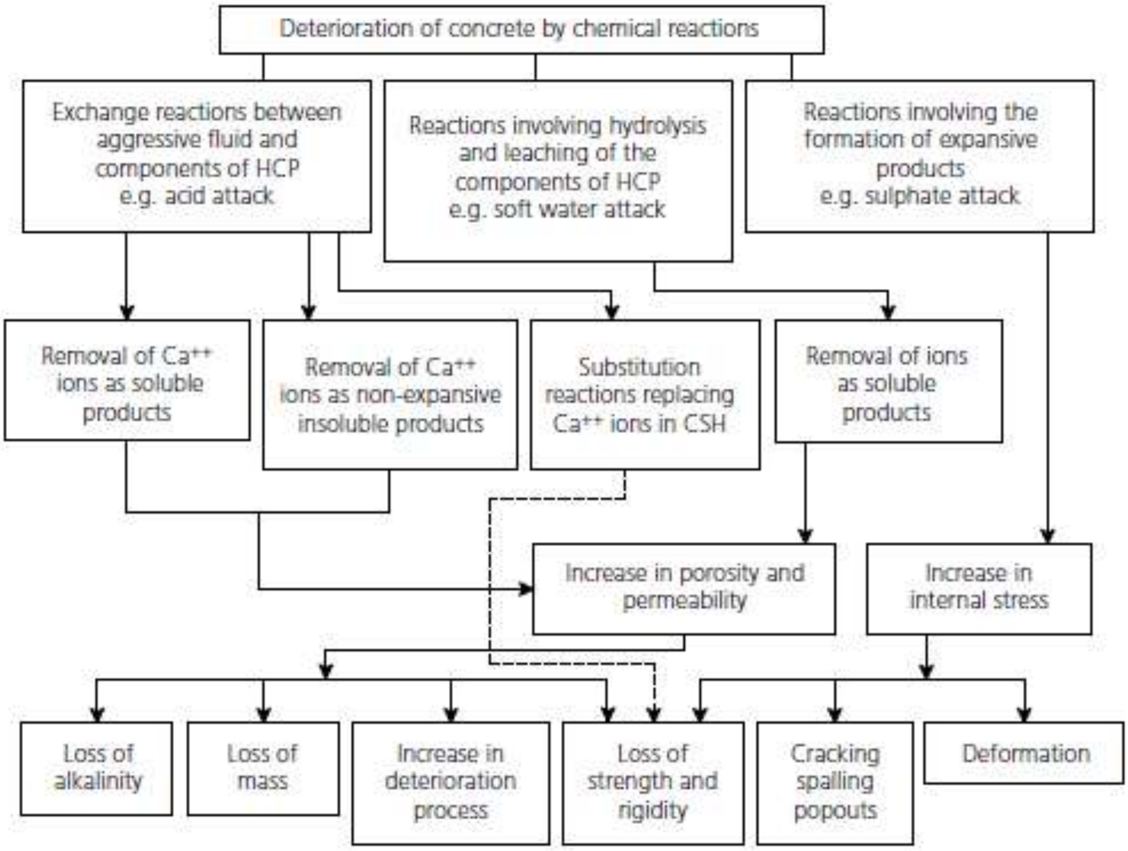

Figure 2-7: Deterioration of Concrete due to Chemical Deterioration Mechanisms (Beushausen et al, 2021)

2.7.2.1 Types of corrosion in Petrochemical Environments

The types of corrosion that are dominant in Petrochemical areas are atmospheric corrosion, galvanic corrosion, stray current induced corrosion and high temperature corrosion. (Garverick, 1994). The most common type when it comes to RC structures would be atmospheric corrosion relating to the ingress of both chlorides and carbon dioxide. Atmospheric corrosion is the corrosion of an element exposed to the atmosphere and its impurities, rather than being fully submerged in a liquid. Atmospheric corrosion can be subdivided into further categories dependent on the atmospheric condition. i.e., dry, damp or wet. There are many ways in which concrete may be subject to deterioration. These may be either physical or chemical means of deterioration, or a combination of both. RC structures' interaction with its environment affects the deterioration process. The deterioration type is primarily based on the aggressiveness of the environment in which the structure is put into service. The intrinsic and extrinsic factors of the concrete play a critical role in the rate at which the concrete begins the deterioration process. The different physical and chemical mechanisms of deterioration experienced in a petrochemical environment include abrasion, erosion, chemical attack, acidic water, saltwater attack, atmospheric gases attack and many others. In the next sub sections the focus will be refined to two leading causes of reinforcing steel corrosion. These are chloride induced corrosion and carbonation induced corrosion.

2.7.2.2 Corrosion of steel reinforcement

Corrosion is defined by the destructive attack of a metal by chemical or electrochemical reaction with its environment. Corrosion of reinforcing steel poses the greatest threat both to the safety and operation of a structure. Understanding all the mechanisms of steel corrosion will help to put good engineering principles into practice. (James, Bazarchi, Chiniforush, Aghdam, Hosseini, Akbarnezhad, Martek. & Ghodoosi, 2019.)

The corrosion of steel reinforcing represents a complex deterioration mechanism that includes both mechanical and chemical processes. This form of deterioration initiates a series of effects, ultimately leading to extreme consequences for concrete structures. As reinforcing steel corrodes, it undergoes expansion due to the chemical alterations it encounters, thereby exerting internal forces that induce expansion within the concrete matrix. This expansion is a driver of structural damage, and its underlying causes justify careful examination.

Steel corrosion is more often an electrochemical process requiring an anode, cathode, electrolyte and a metallic path. These components are called a corrosion cell. These items are most likely always present when steel reinforcing is embedded in the concrete substrate. The steel provides the anode, cathode and metallic path and the concrete in the presence of salts and moisture allows for an acceptable electrolyte. Electrical current flows between the anode and the cathode. The electric current travels from the anode to the cathode. When this flow of electrons occurs, a reaction takes place (James et al 2019).

Corrosion will only take place in the presence of water and oxygen. Where these are limited, the corrosion process is suppressed, and the rate of corrosion is reduced. This is the case in good quality concrete with high alkalinity (PH 12-13) (Emmons 1992). Concrete with a highly alkaline pore solution also protects the embedded reinforcing steel by means of a passivating film layer that bonds to the reinforcing bar. Corrosion will begin once there is damage to the passivated layer. This is as a result of aggressive elements that penetrate the concrete and reach the reinforcing steel layer as shown in figure 2.8 below:

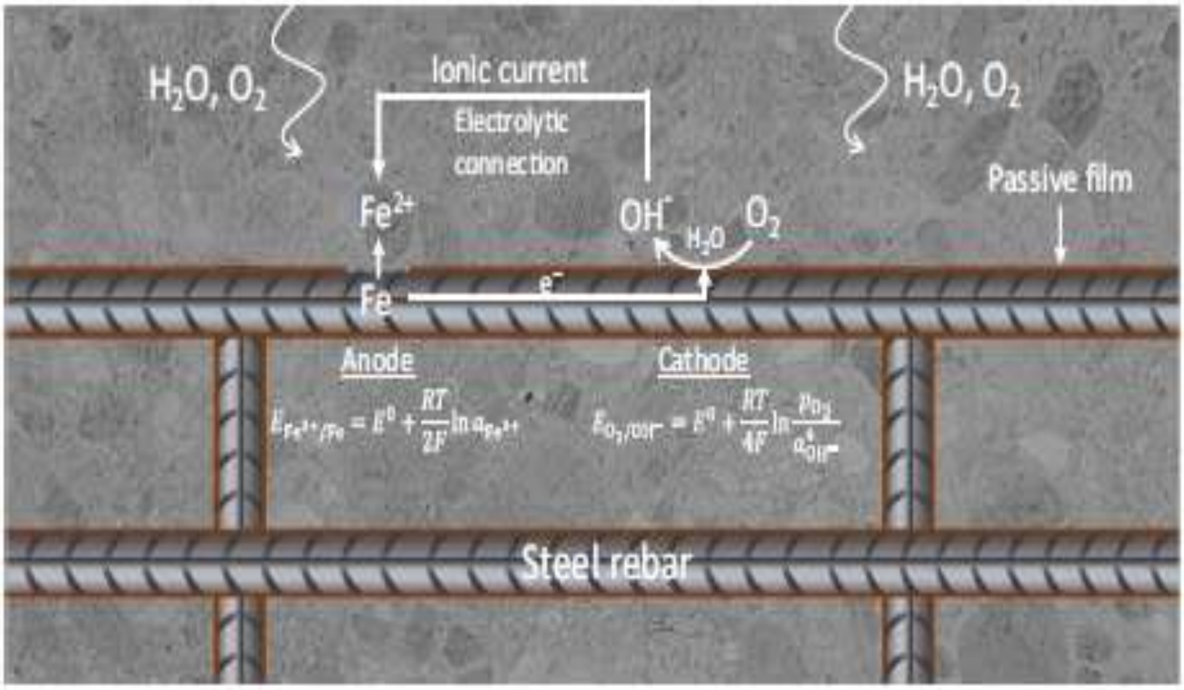

Figure 2-8:Schematic representation of the corrosion of steel in concrete (Rodrigues et al 2020).

Steel corrosion is one of the most destructive mechanisms responsible for causing severe harm to concrete structures. Its destructive effects are extensive, causing damage on two fronts, the reinforcing steel itself and the concrete matrix in which it is embedded. The first factor of this double impact involves the rusting of the reinforcing steel, leading to structural weakening and a loss of load-bearing capacity (Beushausen et al 2021). Simultaneously, the corrosion-induced degradation of steel causes material loss, further weakening the structural integrity of the affected structural components.

In parallel, the concrete matrix also suffers from steel corrosion. The consequences exhibit as a cascade of distressing defects, including delamination, cracking, and spalling. Delamination refers to the separation of layers within the concrete, resulting in reduced bond strength between the concrete and the corroding steel. Cracking occurs as a consequence of the internal stresses generated by the expansion of corroding steel, while spalling refers to the detachment of concrete fragments from the surface, creating aesthetically displeasing and structurally compromising defects (Beushausen et al 2021).

The relationship between steel corrosion and concrete deterioration depends on several underlying factors, including the environmental conditions and specific corrosion mechanisms. Among these mechanisms, carbonation and chloride-induced corrosion emerge as the most prevalent causes contributing to this form of deterioration (Beushausen et al 2021). The succeeding literature will elaborate on the specifics of these processes, explaining their respective mechanisms and their roles in the corrosion-induced degradation of concrete structures.

2.7.2.3 Chloride-induced Corrosion

The ingress of chlorides into concrete stands as a prominent corrosion mechanism in reinforced concrete (RC) structures, exerting a direct and extreme influence on the long-term service life of such structures. Specifically, the infiltration of aggressive agents, particularly chlorides, poses a significant threat. Chlorides play a fundamental role in this corrosion process by depassivating the gamma ferric oxide film that normally protects the surface of reinforcing steel. This depassivation occurrence initiated by chlorides contributes to a localized form of corrosion known as pitting corrosion, which is central to the degradation of concrete structures.

The transport mechanisms explained earlier in this report play a critical role in facilitating the ingress of chlorides through the concrete matrix. In a petrochemical setting where chemicals are continuously produced, there is an atmospheric presence of chlorides. As a result, structures located in such environments are at risk of experiencing accelerated corrosion, primarily attributed to chloride-induced corrosion.

Chlorides in solution move through concretes pore interconnectivity through convection. The chloride ions thereafter travel through the concrete to the steel reinforcement face by the process of diffusion. It is important to note that the ability of concrete to resist the ingress of chlorides is fundamentally linked to its porosity, with more porous concrete structures being particularly susceptible to chloride penetration (Concrete & Australia, 2009).

Chloride-induced corrosion is characterized by pitting corrosion with anodic and cathodic sites. When chlorides are able to penetrate the cover concrete either during casting or after environmental exposure, they have the ability to depassivate the protective layer of the reinforcing steel of the structure. When the chloride concentration at the reinforcing steel is sufficient, they will act as a catalyst to steel corrosion as seen in Figure 2.9 (Rodrigues, Gaboreau, Gance, Ignatiadis and Betelu, 2020).

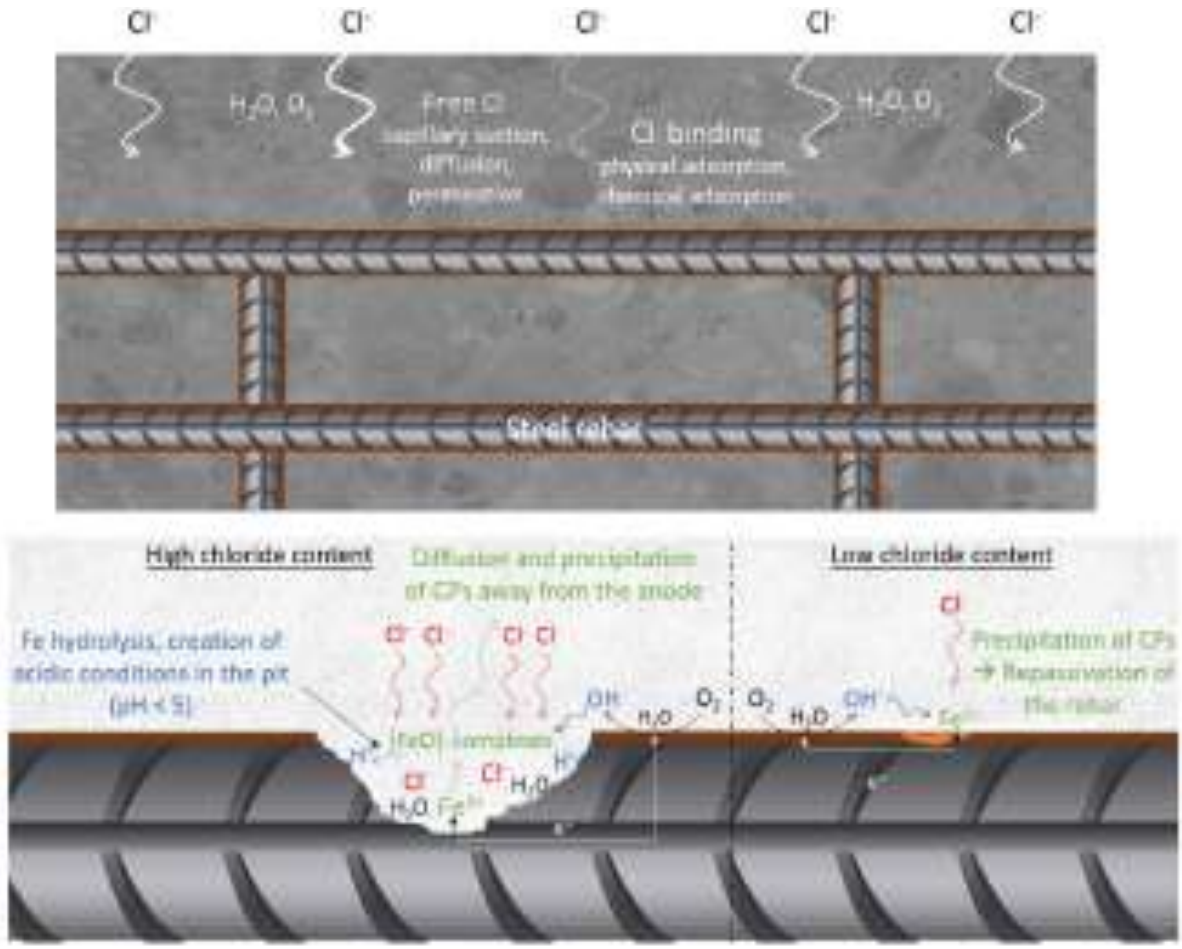

Figure 2-9- Schematic representation of the mechanism of chloride induced corrosion (Rodrigues et al 2020).

In essence, the ingress of chlorides into concrete represents a critical factor in the steel corrosion vulnerability of RC structures, with severe implications for their long-term durability and structural integrity.

2.7.2.4 Carbonation Induced Corrosion

The pH level of concrete is relatively high, normally ranging between 12 and 13, due to the substantial concentration of hydroxides within the concrete pore solution. Among the various substances present in concrete, calcium hydroxide ($Ca(OH)_2$) exhibits partial solubility in the pore solution, with only a fraction of it dissolving into the solution. Consequently, the remaining $Ca(OH)_2$ precipitates and crystallizes within the pore structure of the concrete. This occurrence sets the stage for carbonation, a process in which atmospheric carbon dioxide (CO2) reacts with the available $Ca(OH)_2$ within the concrete, leading to the formation of carbonation products, as expressed by the equation:

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3\ H_2O$............(1)

The carbonation reaction plays a fundamental role in reducing the alkalinity of the pore solution as shown in fig 2.10 below, causing the pH to drop below 9. Once carbonation has neutralized the concrete surrounding the steel to a pH below 9, the protective film around the reinforcing steel undergoes depassivation, initiating the corrosion process (Tantele, Votsis, Danezis, Anastasiou & Georgiou, 2016).

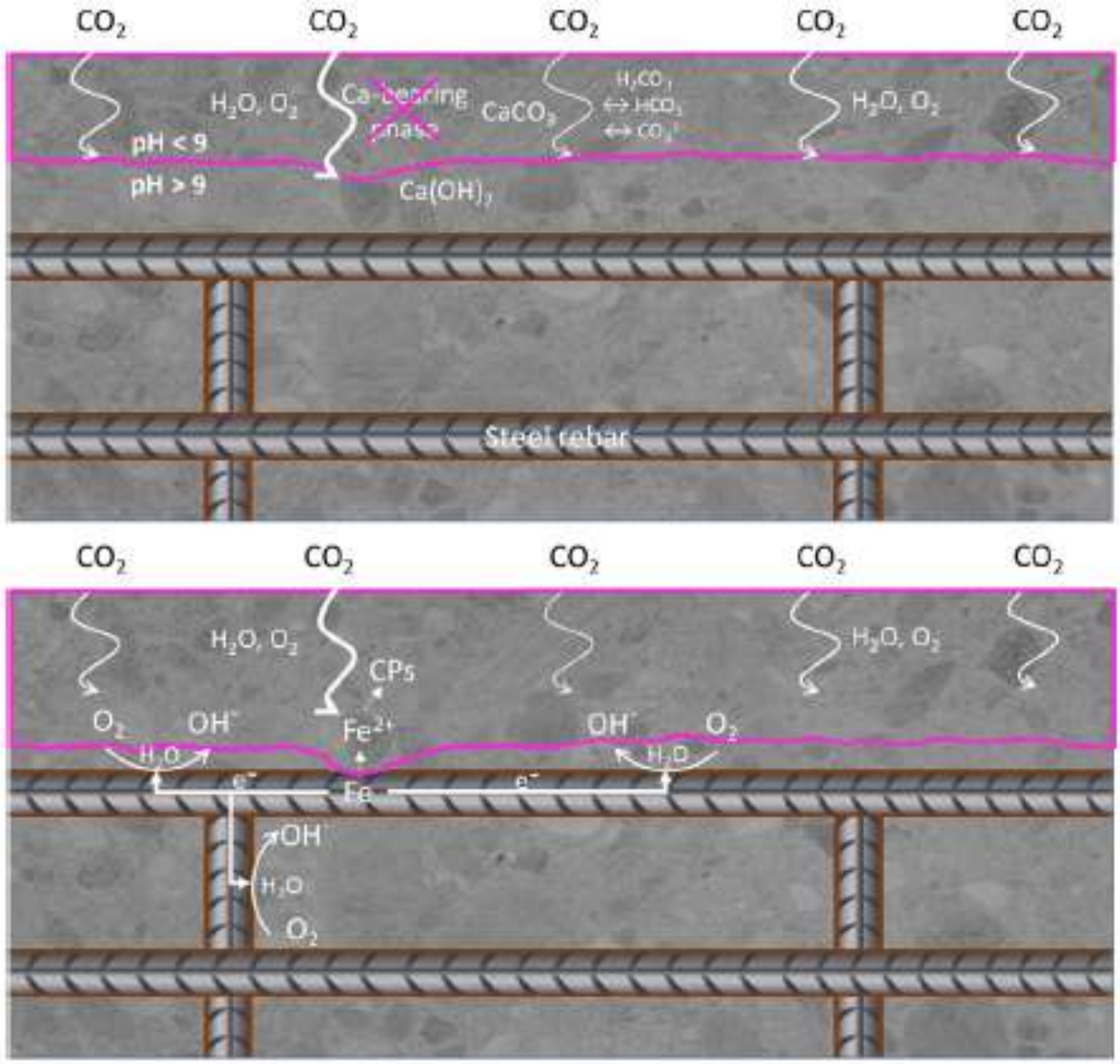

Figure 2-10 – Schematic representation of the mechanism of carbonation-induced corrosion (Rodrigues et al 2020).

The depth of the carbonation is determined by the consumption of all available Ca(OH)2 during the reaction. Evaluating the depth of carbonation is commonly accomplished through petrographic examination, which involves the application of phenolphthalein to extracted cores. In areas with a high pH (above 9), the sample turns pink, while in carbonated areas with a pH below 9, the sample remains colourless.

Carbonation is typically a gradual process due to the relatively low levels of CO2 in the atmosphere (Otieno, Ikotun & Ballim, 2019). However, it may be accelerated under specific exposure conditions, such as elevated temperatures and high relative humidity. Increased temperature expedites the carbonation reaction, making it more pronounced.

In environments comprising multiple reinforced concrete (RC) structures, as often is the case in petrochemical factories, many of these structures are susceptible to carbonation. Certain areas, like boiler blowdown pits, are exposed to exceptionally high temperatures, further accelerating the carbonation process. Given the nature of these environments, the ingress of CO_2 into the concrete is more pronounced. Durability aspects of concrete in a petrochemical environment are critical in determining the concrete's ability to withstand exposure to elevated levels of CO_2. Both intrinsic and extrinsic factor are critical role players in preventing premature ingress of aggressive agents into the concrete.

The overall effect that carbonation has on the concrete structure is that once the steel reinforcement starts to corrode, the structure begins to lose the structural capacity it had when the steel had not corroded. The structure is deemed to be compromised when the steel has lost a significant amount of cross-sectional area. The loss of cross-sectional area leads to an unsafe structure and has failed the serviceability requirements of the structure.

When carbonation occurs in a concrete structure that has the presence of chlorides already present or vice versa, the two processes combine and accelerate the rate of corrosion of the steel in the structure. This happens by accelerating the depassivation of the gamma ferric oxide film on the steel. When carbonation reduces the pH of the concrete it reduces it causes the chlorides that have been chemically bound to become free and available to aid in the depassivation of the steel reinforcement.

2.7.2.5 Sulphate Attack

Sulphate attack involves a chemical deterioration mechanism in reinforced concrete structures, developing severe implications for their structural integrity and long-term durability performance. This harmful process occurs because of the interaction between sulphate ions, commonly found in groundwater or soil, and the components of concrete. The subsequent chemical reactions cause expansive products that apply internal pressure on the concrete matrix, leading to distress in the form of cracking, spalling, and overall structural deterioration (Bentz, 2006).

Sulphate attack manifests in two principal forms: external and internal. External sulphate attack transpires when sulphate ions from the external environment penetrate the concrete. External sources of sulphates can include sulphate-rich soils, saline water, or industrial discharges. When these sulphates infiltrate the concrete, they can react with the hydrated compounds in the cement paste, leading to the formation of expansive compounds like ettringite and gypsum. These expansive products exert pressure on the concrete, causing it to crack, spall, and lose its structural integrity (Neville, 2011). Internal sulphate attack, conversely, arises from sulphate ions that are already present within the concrete's mix, such as the aggregates or cementitious materials used in the mixture. These internally sourced sulphates can react with the concrete over time, especially when there is a moisture source. The reaction between internal sulphates and the cementitious phases can result in the formation of expansive compounds, leading to similar damage as observed in external sulphate attack. (Mindess, Young, & Darwin, 2003).

The severity and progression of sulphate attack depend upon various important factors, including the type and concentration of sulphates, the composition of the concrete mixture, and dominant environmental conditions (Mehta & Monteiro, 2014). Mitigating sulphate attack and understanding its mechanisms are important for engineers and concrete specialists to ensure the extended durability and safety of reinforced concrete structures.

2.7.2.6 Alkali-Silica Reaction (ASR)

Alkali-Silica Reaction (ASR) is a chemical deterioration mechanism in reinforced concrete structures, with significant implications for their long-term durability performance and structural integrity. This harmful process arises from the interaction between alkalis, normally sourced from cement or aggregates, and certain reactive forms of silica present in aggregates used in concrete mixes (Diamond & Dolch, 2012). The result is the formation of a gel-like substance within the concrete, which absorbs water and swells up. This expansion exerts internal pressure on the concrete matrix, leading to the development of microcracks, map cracking, and overall deterioration of the structure (Thomas, 2016).

ASR manifests in two primary forms: internal and external. Internal ASR occurs when the source of alkalis and reactive silica originates from within the concrete mixture itself. External ASR, on the other hand, arises when these reactive elements penetrate the concrete from the external environment, typically through exposure to alkali-rich groundwaters or external sources (Fournier et al., 2015).

The severity and progression of AS” dep’nd on varying factors, including the alkali content in the cement, the type and reactivity of aggregates, temperature, humidity, and the availability of water (Thomas, 2016). Mitigating measures, such as using low-alkali cements or selecting non-reactive aggregates, are essential to mitigate the risk of ASR and ensure the long-term durability of reinforced concrete structures.

2.8 Considerations to Ensure Durability of RC Structures

To ensure the long-term durability of concrete structures, it is important to carefully assess both the concrete’s quality and the specific environmental conditions to which it will be exposed. As emphasized earlier, distinct exposure environments can exert varying influences on concrete structures, necessitating an understanding of their possible effects.

2.8.1 Protecting Concrete Subject to Water-borne Chemical Attack

In the context of natural draft concrete cooling towers, it is common practice to utilize water contaminated with hydrocarbons as part of the cooling process. Sulphides, ammonia, suspended solids, and chlorides are among the contaminants present in the water (Reddy et al, 2020). This water is stored in a cooling tower pond and subsequently evaporates into the atmosphere as it passes through the tower. Addressing the deterioration resulting from this form of chemical attack involves implementing specific strategies, including:

1. Enhancing the internal properties of the concrete: This entails optimizing the concrete mixture design, selecting appropriate types of cement, and applying protective coatings to bolster the concrete’s resistance to chemical attack. Optimizing the concrete mix design to enhance its resistance to water-borne attack (Beushausen et al 2021). This involves carefully selecting cement types, aggregates, and additives that are less susceptible to chemical reactions with water.

2. Quality Assurance: Implementing stringent quality control measures during the concrete placement and curing processes ensures a denser, more impermeable concrete matrix (Neville, 2011).
3. Environmental Management: Another approach to mitigating deterioration is to alter the conditions to which the concrete is exposed. However, in the context of a petrochemical factory, this method may prove exceedingly challenging due to the continuous operations and emissions from various other plant processes. In cases where the concrete is subjected to aggressive water-borne substances due to environmental conditions, managing the exposure environment should be considered (Ropital, 2009). This involves controlling water quality or drainage, especially in industrial settings where water composition is under human influence.
4. Protective Coatings and Surface Treatments: Utilization of protective coatings and sealants specifically designed to resist water-borne attack. These coatings act as an additional layer of defence against chemical reactions and physical wear, extending the life of the concrete (Mindess, Young, & Darwin, 2003).
5. Regular Maintenance and Inspection: Implement a robust maintenance program to monitor the condition of the concrete over time. Cyclic inspections can identify early signs of deterioration, allowing for appropriate repairs or maintenance actions to prevent further damage (ACI Committee 201, 2008).

Applying a combination of these strategies, adapted to the specific circumstances of the concrete structure, can significantly improve its resistance to water-borne attack and extend its service life.

2.8.2 Protecting Concrete Subject to Air-borne Chemical Attack

Similar to water-borne attack, protecting concrete structures from air-borne attack is essential for ensuring their long-term durability and performance. Air-borne attack encompasses various forms of deterioration, including chemical reactions with pollutants and physical wear due to wind-driven particles. Implementing effective protective measures is essential.

The Sasol Secunda petrochemical facility is located within an aggressive environmental setting, as described by Beuhausen et al. 2021. This petrochemical factory involves diverse industrial activities, including fossil fuel combustion, power generation, refinery operations, and the operation of multiple chemical plants. Within this context, concrete structures are exposed to detrimental gas emissions that have a harmful impact on their integrity. The composition of the atmosphere in this industrial atmosphere is inherently corrosive, owing to the various by-products discharged into the air.

The deterioration of reinforced concrete structures, particularly in industrial settings like petrochemical plants, is a concern due to the corrosive nature of certain gas emissions. Sulfur dioxide (SO_2) and nitrogen oxides (NOx) are major contributors to this issue, as they react with water to form sulfuric and nitric acids, respectively. These strong acids can readily dissolve concrete, compromising its structural integrity. Additionally, carbon dioxide (CO_2) forms carbonic acid when combined with water, which, although weaker than sulfuric and nitric acids, still contributes to concrete degradation over time. Hydrogen chloride (HCl) and ammonia (NH_3) also pose risks, as they form hydrochloric acid and ammonium hydroxide upon reacting with water, further exacerbating the corrosive environment for concrete structures.

In the pursuit of ensuring durability, it is imperative to account for both the geographical location and the prevailing meteorological conditions of this environment as integral components of the design process.

A few strategies that can be employed to protect structures subject to air-borne attack are highlighted below:

1. Surface Coatings and Sealants: Applying protective coatings and sealants to the concrete surface. These coatings act as a barrier against airborne pollutants and particles, reducing the possibility for chemical reactions and physical damage (Mehta & Monteiro, 2014).

2. Corrosion Inhibitors: Incorporate corrosion-inhibiting admixtures into the concrete mixture. Admixtures can help abate the impact of air-borne corrosive pollutants, such as sulphur dioxide and chlorides, on the concrete and embedded steel reinforcement (Nawy, 2014).

3. Regular Cleaning and Maintenance: Routine cleaning and maintenance program could be initiated to remove collected airborne contaminants from the concrete surface. This prevents the accumulation of corrosive substances and particulate matter (ACI Committee 201, 2008).

4. Environmental Management: Areas exposed to air-borne pollution, implementing environmental management measures could be considered. These could include reducing emissions from nearby industrial sources, controlling airborne pollutants, or the relocation of critical structures to less polluted areas.

5. Protective Barriers: In corrosive environments, installing physical protective barriers, such as screens or shields, to minimize the direct impact of airborne particles and pollutants on the concrete surfaces could be considered.

By using a combination of these strategies, tailored to the specific environmental challenges faced by the concrete structure, it is possible to improve its resistance to air-borne attack and extend its service life considerably.

2.8.3 Protecting Reinforcing Steel against Corrosion

Protecting reinforcing steel against corrosion in concrete is a fundamental aspect of ensuring the long-term durability and structural integrity of reinforced concrete structures. Corrosion of the steel reinforcement is a pervasive issue that can compromise the load-bearing capacity and safety of these structures. Therefore, the implementation of effective corrosion protection strategies is essential in mitigating this threat.

The chosen approach for protection against the corrosion of reinforcing steel depends on the supply of high-quality cover concrete, ensuring the realization of the structure's intended service life. Various methods exist to protect embedded reinforcing steel, with corrosion predominantly occurring due to depassivation of the steel surface. To counter this depassivation process and protect the steel, one approach involves the application of protective coatings on the reinforcing bars (Beushausen et al 2021). These coatings promote passivation, thereby contributing to the fulfilment of service life requirements.

Another method for preserving reinforcing steel is the use of corrosion-resistant steel materials. Stainless steel and epoxy-coated reinforcing are examples of such materials that offer enhanced resistance to corrosion. These materials possess inherent resistance to the corrosive agents commonly encountered in concrete environments, thus significantly extending the service life of the steel reinforcement (Thomas, 2016). These materials, however, are significantly more costly.

The use of cathodic protection systems can also be installed to protect reinforcing steel against corrosion. Cathodic protection involves the application of a direct or indirect electrical current to the steel reinforcement, which alters the corrosion process from anodic to cathodic reactions. This method actively suppresses corrosion by preserving the steel's electrochemical stability (Andrade et al., 2018). This is achieved by applying coatings of a metallic nature that will provide an anodic site thereby protecting the steel. The use of cathodic protection is highly beneficial provided they are designed and placed correctly, and their use should be considered in the conceptual design stages of the project.

It is essential to emphasize that the effectiveness of these methods depends on the careful preparation of the steel surface to ensure a strong bond between the applied product and the reinforcing steel. Equally important is the bond between the "newly coated" steel and the surrounding concrete. Therefore, the selected protective coatings must demonstrate the ability to bond effectively to the concrete surface. An assessment of the environmental conditions to which the steel reinforcement will be exposed is necessary, to establish the appropriateness and effectiveness of the chosen protective coatings in preventing deterioration.

2.9 Chapter Summary and Closure

Oil refineries and petrochemical factories operate with intricate processes reliant on large equipment, often supported by large structures of structural steel and reinforced concrete. However, these structures face significant challenges due to exposure to aggressive mediums such as hydrocarbons, gases, and corrosive acids, leading to degradation. Premature steel corrosion is identified as the primary risk factor for structural failure in these environments.

Durability factors, including aggregate quality, cement content, water quality, and concrete permeability, play crucial roles in the resilience of these structures against aggressive environmental factors. Addressing these factors during the conceptual phase of a project is vital to ensure the structure's intended service life.

To evaluate durability performance and ensure concrete quality, South Africa has developed three durability index (DI) tests, measuring water sorptivity, chloride conductivity, and gas permeability. These tests serve as guides for specifying concrete quality and predicting service life. While developed and validated in laboratory settings, they have not been extensively applied to existing structures under normal site conditions. Investigative efforts aim to determine the feasibility of employing these tests on-site to enhance durability specifications.

Durability Index (DI) tests conducted on mature concrete structures provide valuable insights into their long-term durability performance potential. These tests evaluate key transport properties, such as oxygen permeability and chloride conductivity, which directly influence concrete deterioration mechanisms.

Durability index testing on mature structures can inform future design parameters, facilitating the optimization of concrete mixes and construction methods based on in-situ as-built performance feedback. The results can also guide targeted improvements in construction specifications to ensure long-term concrete durability. The data obtained from DI tests on mature structures can also inform repair strategies, enabling data-driven decisions for effective remedial actions based on concrete quality assessment.

Lampacher (2000) proposed a framework for evaluating the long-term performance of mature concrete structures by integrating early-age DI tests with periodic direct performance monitoring. This approach involves comparing early-age DI results with subsequent measurements and direct in-service durability performance data, leading to a comprehensive understanding of the concrete's durability performance trajectory throughout its service life. By utilizing this framework, engineers can make informed decisions regarding maintenance, repair, and future construction practices to enhance the durability and longevity of concrete structures.

Environmental exposure conditions significantly influence the durability of reinforced concrete structures, emphasizing the need for engineers to understand and address these conditions in early design stages. Concrete degradation poses significant sustainability and safety concerns, particularly in challenging environments like power generation and petrochemical plants. Despite concrete's historical preference for durability in construction, its limitations are influenced by various factors, including material properties, design considerations, construction methods, and environmental exposure, which can accelerate deterioration.

Concrete deterioration mechanisms, such as alkali-aggregate reactions, freeze-thaw cycling, and steel corrosion, merit comprehensive investigation and consideration for concrete durability. Among these mechanisms, steel corrosion, particularly through carbonation and chloride-induced processes, stands out as a prevalent concern in reinforced concrete structures within aggressive industrial environments. Addressing these mechanisms effectively is essential for ensuring the long-term viability and safety of civil infrastructure.

The next chapter will cover the experimental setup and methodology used in this study.

3. METHODOLOGY

3.1 Introduction

This chapter details the methodology employed to investigate the in-service durability performance and deterioration mechanisms of a natural draft reinforced concrete cooling tower operating within the harsh petrochemical environment of the Sasol Secunda Synfuels facility. The assessment encompasses a multi-faceted approach, integrating on-site visual inspections, non-destructive testing (NDT), core sample extraction, and subsequent laboratory analyses. These methods collectively aim to provide a comprehensive understanding of the factors influencing the durability of the cooling tower and to identify the primary mechanisms contributing to its deterioration.

The on-site investigations commenced with a preliminary visual assessment conducted from ground level, followed by detailed hands-on surveys of the cooling tower's exterior surfaces. Non-destructive testing (NDT) was then employed to assess the condition of the concrete and reinforcement. Based on the findings of these initial assessments, specific core locations exhibiting visible signs of deterioration were identified for extraction.

The extracted core samples were transported to the University of the Witwatersrand Civil Engineering durability laboratory for further analysis. Laboratory testing included the application of three Durability Index (DI) tests: the Oxygen Permeability Index (OPI), Water Sorptivity Index (WSI), and Chloride Conductivity Index (CCI). These tests aimed to quantify the concrete's resistance to oxygen diffusion, water ingress, and chloride ion penetration, respectively, providing crucial insights into the material's durability performance.

By combining the results of on-site assessments and laboratory analyses, this study seeks to establish a comprehensive understanding of the in-service durability of the Sasol Secunda cooling tower. The findings will contribute to the development of effective maintenance and repair strategies, ultimately enhancing the longevity and safety of cooling towers operating in similar aggressive environments.

3.2 Historical Data

In order to comprehensively assess the condition of the cooling towers, it is imperative to compile all pertinent as-built documentation. This documentation encompassed structural information, previous inspection reports, approved for construction (AFC) drawings, as well as environmental and service data. The historical data was sourced from the Sasol document database.

The Sasol Secunda Synfuels facility houses eight natural draft cooling towers constructed of reinforced concrete with hyperbolic thin shell designs. The shell thickness varies along the height of the tower with a maximum thickness of 910mm at the bottom skirt of the tower, 590mm at the top rim and a minimum thickness of 180mm at approximately mid-height of the tower. These cooling towers have been in operation since the early 1980s, with four dedicated to process water cooling, referred to as "process water cooling towers" or "PWCT" shown in Figure 3-1, and four serving power generation, referred to as "utility towers". For clarity, throughout this research report, these towers are identified using shorthand notation indicating the unit number and the specific tower; for example, "245A" means PWCT Tower A at Unit 245, denoted as 245CT101A.

The West Factory, including PWCTs 045A and 045B, was constructed and began operations around 1980. Subsequently, the East Factory, comprising PWCTs 245A and 245B, was built and commissioned in 1982. The focus of this study is PWCT 245B, selected due to its representative nature of the observed deterioration patterns across the process water cooling towers.

Over the years, all eight towers have experienced varying degrees of concrete deterioration, with the process cooling towers generally exhibiting more severe deterioration than the utility towers. The deterioration in the process cooling towers is characterized by cracking, delamination, spalling of concrete, and softening and erosion of the cement paste matrix, often linked to the corrosion of embedded reinforcing steel.

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Figure 3-1 – Location of Cooling Tower 245B within the Sasol Secund complex (Google Earth)

The concrete deterioration in the process cooling towers is characterized by cracking, delamination, and spalling of concrete, often linked to the corrosion of embedded reinforcing steel. Furthermore, areas of softening and erosion in the cement paste matrix have been observed. In response to this deterioration, a series of concrete repairs for the PWCTs were initiated in the early 2000s. These repairs were typically focused along the upper rims and the uppermost 10 meters of the exterior shell wall and included the application of a polyurethane waterproofing coating on the external surface.

However, deterioration in the PWCTs has continued to increase over time, with a significant increase in deteriorated areas observed since 2010. In 2013, owing to the increasing requirement of concrete repairs, Sasol initiated a renewal capital concrete repair project for the four PWCTs, with particular emphasis on repairing the two Unit 245 PWCTs. The project specifications for the renewal capital repair project specified conservative concrete patch repairs for areas with delaminated and spalled concrete, localized use of corrosion inhibitors and/or galvanic anodes, and the application of a protective coating to the exterior of the tower shell wall.

Concrete repairs to Cooling tower 245A were being executed however, the project was halted in July 2017 due to commercial disputes with the appointed Contractor. At the time of work interruption, concrete repairs had been partially completed, covering approximately 70 percent of the tower's upper height, and a protective coating had been applied. In addition, the work interruption left several concrete excavation areas open, exposing reinforcing steel at numerous locations on the lower 30 percent of the tower shell height.

Repairs for Tower 245B were initially intended to adhere to the same specifications as those for Tower 245A, and these repairs are ongoing. Nevertheless, questions have arisen regarding the appropriateness of the specified repair methods, and previously undisclosed conditions have come to light during the project's execution. As of the date of this research report, this repair project remains active.

3.2.1 Location

The Natural Draft Cooling Towers under study are situated in Secunda, a town strategically developed amongst coal mines within the Mpumalanga province of Southern Africa shown in Figure 3-2. The origin of this town's name is traced back to its historical significance as the site of the second Sasol refinery, with "Secunda" being a Latin term signifying "second." Sasol's first refinery was established in Sasolburg.

Secunda's geographic location is approximately 140 kilometres west of Sasolburg, located within the Free State province of South Africa. Furthermore, it is approximately 150 kilometres away from Johannesburg, situated in the Gauteng province of South Africa.

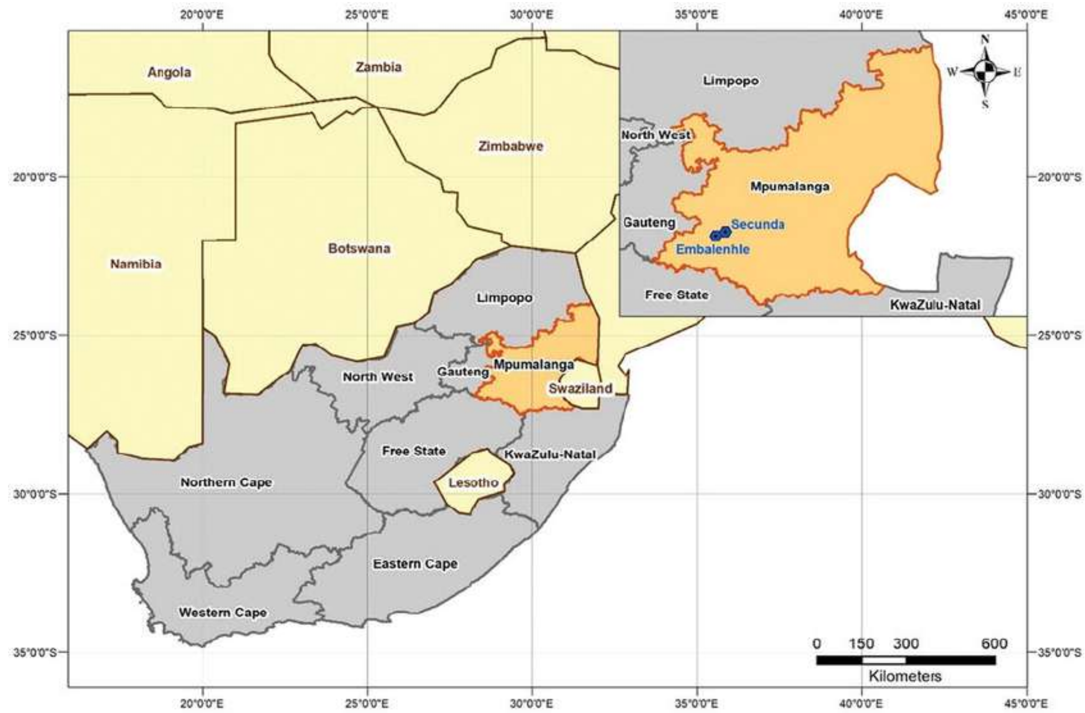

Figure 3-2: Aerial Map of South Africa highlighting the Mpumalanga province (Wright et al 2024),

In terms of climate, the Secunda environment during the summer months, is characterized by an average temperature of 26.5°C. However, the winter season introduces colder nights often accompanied by frost, with temperatures occasionally plummeting to as low as -10°C in low-lying areas during extreme conditions. Winter days are marked by dry, sunny conditions, with an average daytime temperature of 16.2°C.

Sasol's environmental impact is notable, as it was identified as the leading carbon emitter in South Africa in the Carbon Disclosure Project's JSE 100 Report for 2011. The company was found to release 61.2 million metric tons of CO_2 annually, a statistic disclosed by the National Business Initiative. This report was made public during the United Nations' 17th Conference of Parties (COP17) climate change discussions held in Durban, South Africa.

Understanding the environmental impact that the Sasol Secunda complex has on the environment is a critical step in identifying the environmental exposure class that the Cooling Towers fall into. Characterizing the environment therefore becomes an important task of this study.

3.2.2 Structure Description

As per the original design drawings, the as-built PWCT (Process Water Cooling Tower) shell stands at an approximate height of 140 meters, with a skirt diameter of 105 meters and a throat diameter of 65 meters. The construction of the shell wall involved 116 lifts, with its thickness varying according to its height. The thickness at the skirt is 910mm, narrows down to 180mm at the tower's midpoint and ending in a thickened upper section measuring 590 mm at the top rim.

The shell is reinforced through a matrix of meridional (vertical) and circumferential (horizontal) mild steel reinforcing bars situated on both the interior and exterior surfaces. Circumferential steel is nearest to the surface for each mat of steel and these bars are typically size Y10. The design stipulates a concrete cover of 40 mm for each reinforcing bar matrix, and the intended concrete compressive cube strength is set at 30 Mpa.

Support for the PWCTs is provided by a total of 40 pairs of inclined reinforced concrete columns called raking columns, each characterized by an 850-mm square cross-section. These columns are approximately 15.2 meters in length and are strengthened with longitudinal steel reinforcing, predominantly using Y25 bars accompanied by Y10 and Y12 steel lateral ties. The design specifications call for a concrete cover of 50 mm for the columns, with the design concrete compressive cube strength specified at 35 Mpa.

3.3 Exposure Environment

The environmental conditions surrounding the Sasol Secunda cooling towers are a critical factor in their durability performance. The presence of various industrial processes, including fossil fuel combustion, power generation, refinery operations, and chemical plants, creates a harsh environment characterized by aggressive chemical emissions and airborne pollutants. These emissions, which can include chlorides, sulfates, carbon dioxide, and various acids, pose a significant threat to the concrete's integrity.

The environmental conditions surrounding a cooling tower play a pivotal role in its durability and service life. In this study, a comprehensive analysis of the cooling water chemistry and airborne emissions was conducted to assess the aggressiveness of the environment surrounding the Sasol Secunda Natural Draft Cooling Tower. This assessment considered both the atmospheric emissions from surrounding plants and the aggressiveness of the cooling water used within the tower. The cooling water, which is contaminated with hydrocarbons, sulfides, ammonia, suspended solids, and chlorides, plays a crucial role in the deterioration process.

A thorough analysis of the cooling water chemistry was performed to determine its potential to degrade concrete. This analysis, detailed in Chapter 4, revealed high levels of chlorides and sulfates, indicating a highly aggressive environment.

In addition to the aggressive cooling water, the petrochemical environment surrounding the cooling tower contributes to its deterioration. Airborne emissions from various process plants, including sulfur dioxide, nitrogen oxides, and particulate matter, can be carried by wind and deposited on the cooling tower's surface. These pollutants can react with the concrete, leading to chemical attack, surface erosion, and accelerated degradation.

To quantify the aggressiveness of the environment, the BS EN 206-1:2000 standard was employed. This standard provides a framework for classifying the exposure conditions of concrete structures based on the potential risk of deterioration. The classification considers various factors, including the presence and concentration of aggressive chemical species, temperature, humidity, and wetting and drying cycles.

Based on the combined analysis of cooling water chemistry and airborne emissions, the environment surrounding the cooling tower was classified as a combination of XD1, XD2, and XD3.

- **XD1:** This classification signifies a high risk of deterioration due to the presence of airborne chlorides, leading to corrosion of embedded steel. The high chloride levels found in the from adjacent plants justify this classification for areas in direct contact with the surround environment.
- **XD2:** This classification indicates a high risk of deterioration due to the combined presence of industrial waters and chlorides in the environment. The elevated levels of both chlorides in the industrial water and sulfates from airborne emissions warrant this classification for areas exposed to both water and air.
- **XD3:** This classification denotes a high risk of deterioration due to the combined effects of chlorides, sulfates, and wetting and drying cycles. The presence of chlorides and sulfates in high concentrations, along with the wetting and drying cycles experienced by the cooling tower, justifies this classification for certain sections of the tower.

Understanding the specific environmental classifications for the cooling tower is essential for tailoring appropriate repair and maintenance strategies. The degree of aggressivity necessitates different approaches to mitigate deterioration and ensure the long-term durability of the structure.

3.4 Field Investigation

3.4.1 Visual assessment

The visual assessment is generally the first step to carry during an investigation and is often the most informative step of the investigation. It is during this assessment where the major causes of deterioration and damage are identified, for example if there is concrete that is visually spalling and/or delaminating, this can be used as an indication of the degree of damage (Beushausen et al 2021). The purpose of this visual assessment survey is to conduct a detailed examination of near-surface conditions that are not discernible through conventional visual inspections conducted from ground level.

These conditions include defects such as the identification of cracks, abrasion, spalling, delamination, surface discoloration, joint deficiencies, change in member shape and textural features. Some of the observed defects may be related to material degradation, others to structural performance and in some cases material degradation can affect the structural performance (Beushausen et al 2021).

The scope of this study is limited to the exterior shell due to operational constraints, preventing access to the interior of the tower shell while it remains in operation. The visual assessment survey, an important aspect of this study, comprises the following elements:

1. **Visual and Sounding Assessment (Hammer Testing):**
    - This assessment includes all elevations extending over the height of the tower shell and spans a minimum width of 3 meters which is the width of the working platform.
    - The visual inspection process includes sounding or hammer testing, which involves gently striking the surface to identify potential subsurface defects or irregularities.
2. **Reinforcement Cover Survey (Cover Meter):**
    - This procedure is carried out across all elevations spanning the height of the tower shell.
    - The cover meter is used to measure the depth to the horizontal circumferential steel reinforcement at each lift, enabling documentation of reinforcement depth and locations.

These visual assessment techniques enable an evaluation of the concrete structure, enabling the detection of near-surface defects and providing insights into the placement of reinforcing steel, which allowed for the strategic demarcation for core extraction. Core locations were determined by the the detection of visibly deteriorated concrete as well as concrete that exhibited signs of near-surface defects such as cracking, spalling and erosion. It is important to highlight that, in light of the tower's ongoing operation, the hands-on assessment is exclusively conducted on the exterior shell.

3.4.2 Core Extraction

For the purpose of this study and the on-site repair works, the CT was divided into four quadrants, as depicted in Figure 3-3. The numbers on the circumference of the cooling tower in Figure 3-3 refer to the Temporary Support Platforms (TSPs) used to access the shell surface. For this study, the CT was divided into three levels: Upper (Lift 68 to Lift 116), Middle (Lift 21 to Lift 67), and Bottom (Lift 1 to Lift 20).

Core samples were extracted from each quadrant at various heights using temporary support platforms (TSPs) attached to guy ropes anchored to the top rim of the tower (Figure 3-5). The specific guy ropes used for core extraction are detailed in Chapter 4. A total of 48 cores were extracted, with 12 cores taken from each quadrant (4 cores per level). Figure 3-7 shows the TSPs being supported by their associated guy ropes.

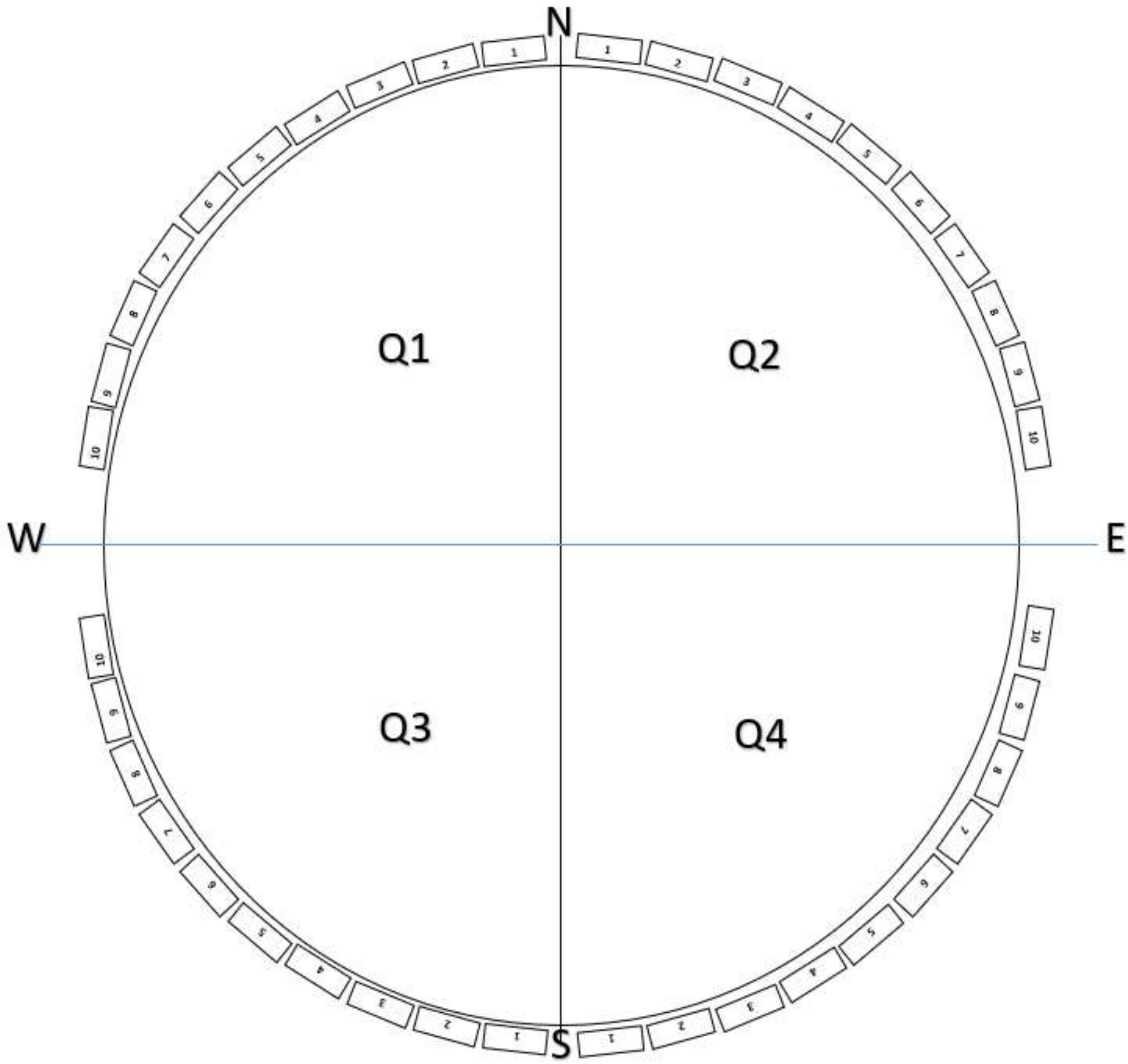

Figure 3-3 – Plan view of the tower depicting the four quadrants and the TSPs per quadrant.

The extracted cores were visually assessed to document their condition before being transported to the laboratory for further analysis. The visual assessment included examining the external and internal surfaces of the cores for cracks, voids, discoloration, aggregate distribution, and signs of reinforcement corrosion.

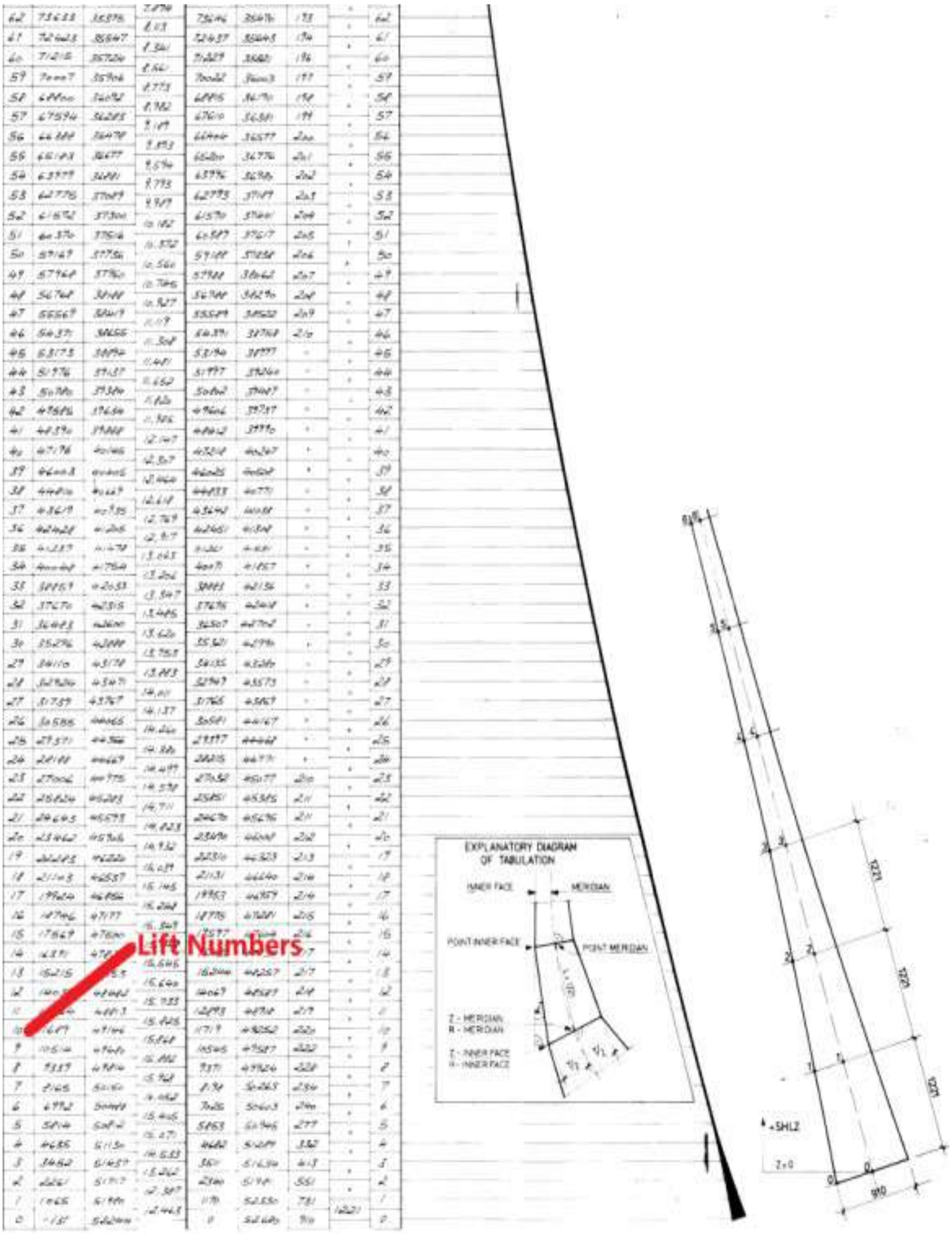

Figure 3-4 – Section through the Cooling Tower showing the lift numbers.

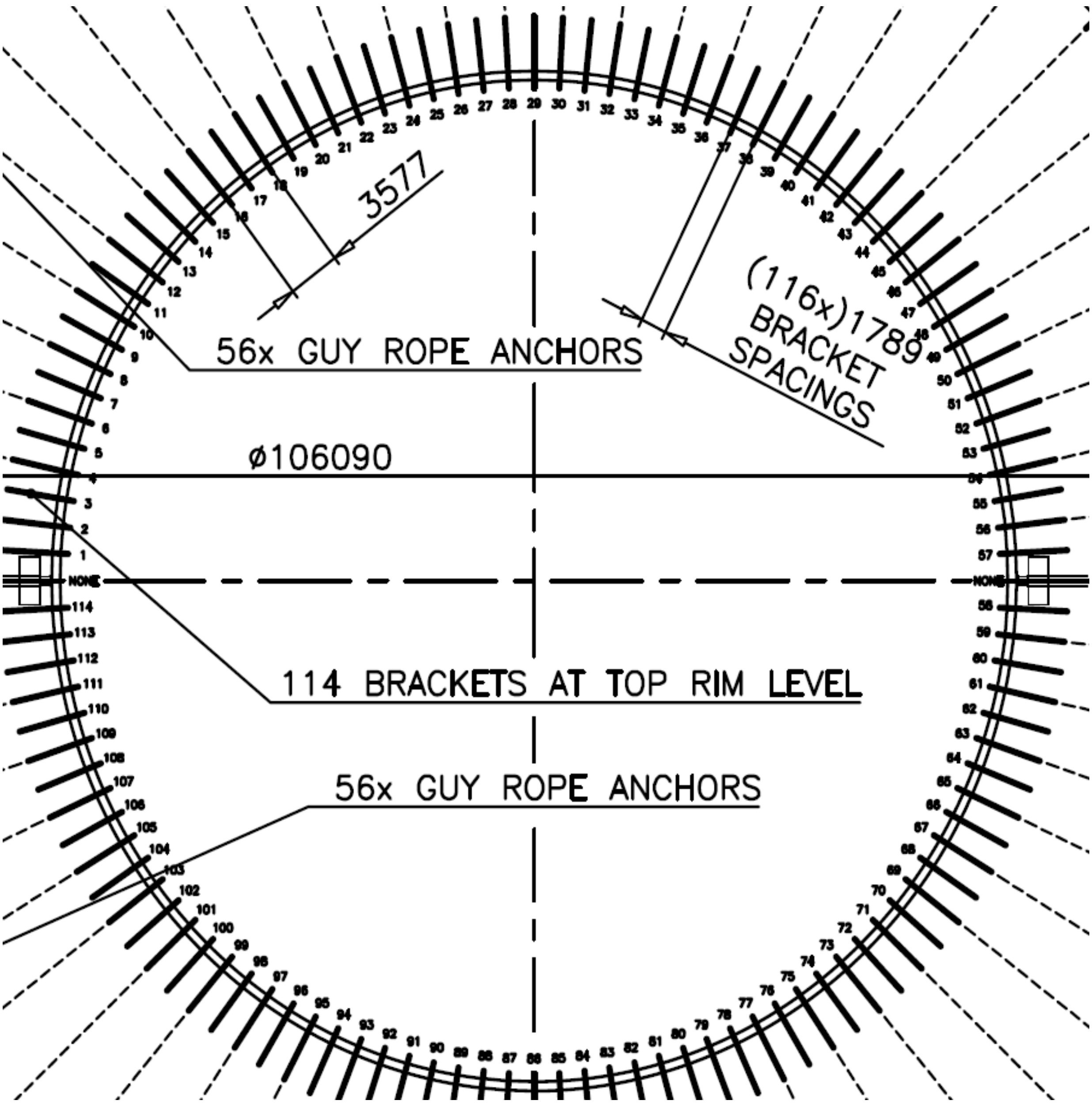

Figure 3-5: Depiction of guy ropes used to support the Temporary Support Platforms

To enable the extraction of the cores from the tower shell, the guy ropes serve as enablement to provide safe access to the shell surface. Attached to the guy ropes are the access platforms on which the work is carried out. Depicted in Figure 3.6 below is the anchor detail of the guy ropes on to the shell surface to allow the TSPs to safely move up and down the shell surface. For the purpose of this study, the guy ropes enabled the successful extraction of the cores required for laboratory testing.

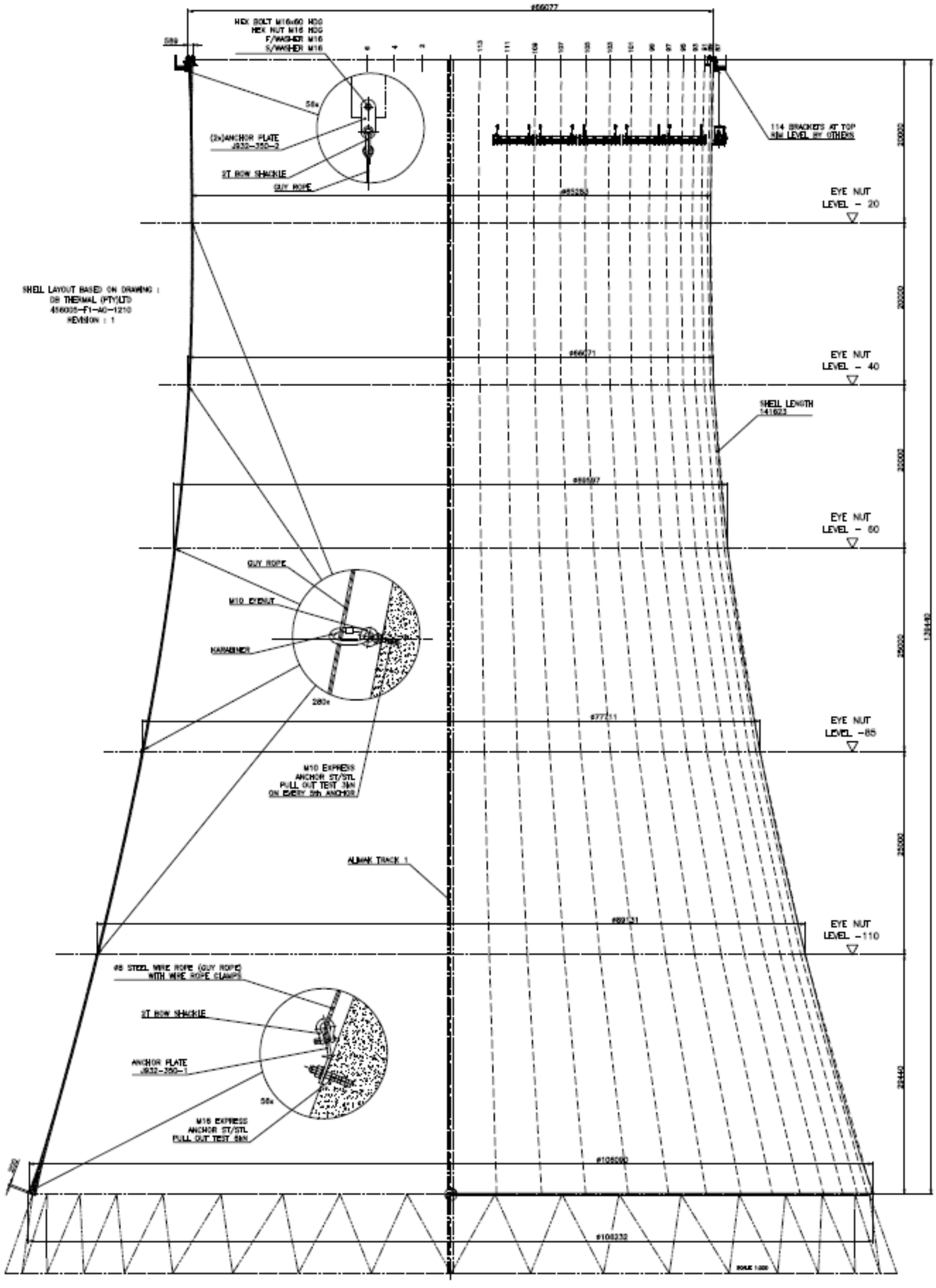

Figure 3-6: Visual Representation of guy ropes and their anchors at the top rim of the tower

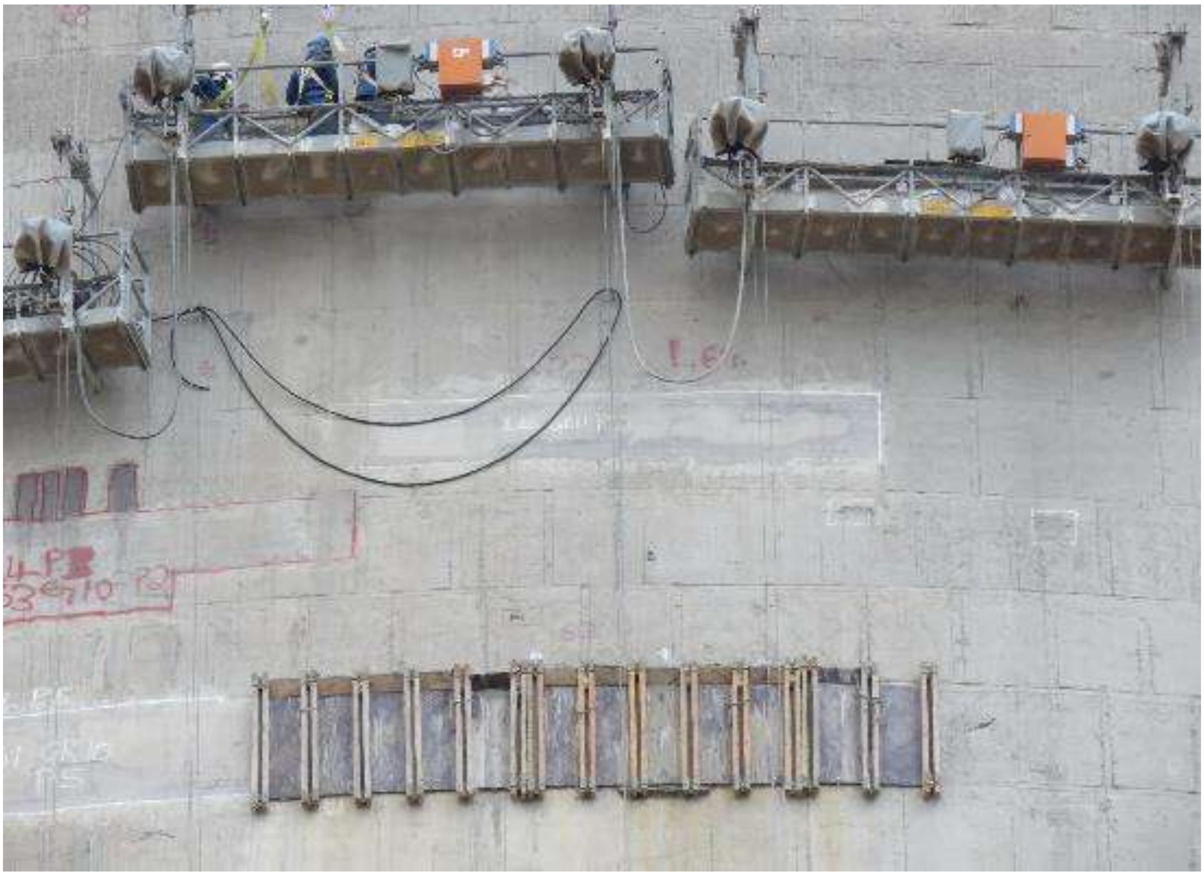

Figure 3-7: TSPs being supported by their associated guy ropes.

Core samples will be used to conduct laboratory analysis with a focus on assessment of the durability performance of the CTs by conducting the three Durability Index tests. The core sampling strategy devised as part of this assessment includes the following key considerations:

1. ***Spatial Distribution of Cores:***
    - Twelve core samples were strategically spaced along the height of the tower within each quadrant. The tower's access systems facilitated entry into all four quadrants, ensuring a comprehensive and representative sampling approach.
2. ***Target Defective Areas :***
    - The selection of core sampling locations was reliant on the presence of visible defects on the concrete structure. Areas exhibiting visible signs of deterioration, such as cracks, spalling, or discoloration were prioritized for core extraction.
3. ***Core Barrel Size Selection:***

- The core barrel size that was used for the core extraction was 100mm. The utilization of a standard core barrel size of 100mm was deemed suitable for adequately assessing the concrete quality and contamination.

4. ***Reinforcement Detection and Mitigation:***

- Care was taken to minimize damage to reinforcing bars (rebar) during the core extraction process as shown in Figure 3.8. This was done through the use of Ground Penetrating Radar (GPR) scanning technology to detect the presence and approximate location of reinforcing steel within the concrete. Core extractions were strategically positioned to minimize interference with the reinforcing as far as possible.

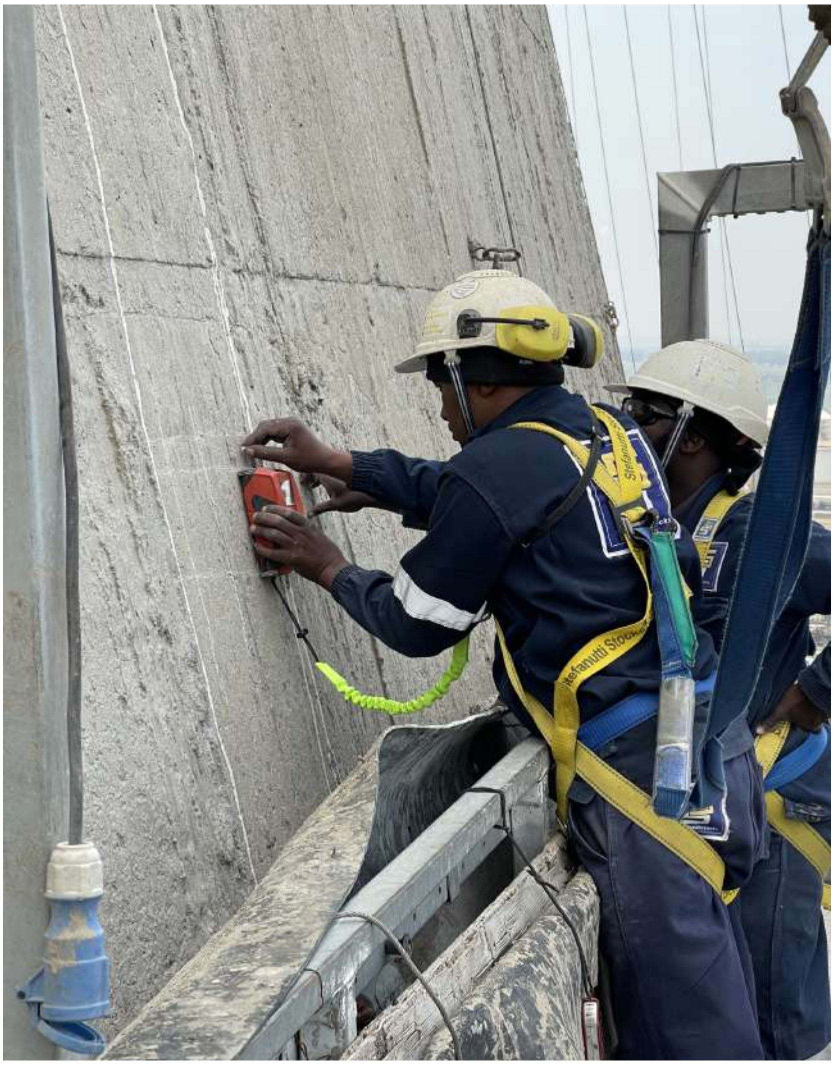

Figure 3-8: Contractor using GPR Technology to identify the location of Reinforcing bars.

The intent of these guidelines is to extract cores that provide valuable understandings into the concrete structure's condition and durability, while at the same time preventing damage to reinforcing steel bars.

3.4.2.1 Visual Assessment of Cores

A visual assessment of the concrete cores is a significant step in evaluating the quality, durability, and structural integrity of concrete elements. The visual assessment and evidence of degradation followed the guidelines that define damage in terms of appearance, location and cause. The assessment was carried out by following the guidelines defined in (Kay, 1992):

- Conduct a visual inspection of the core, both the external face and internal face of the core.
- Examine the external surface for signs of distress, such as cracks, spalling, discoloration, and rust stains.
- Inspect the internal structure of the core for any anomalies, such as voids, honeycombing, or segregation.
- Assess the surface texture and finish of the core, looking for irregularities, roughness, or variations from the expected finish.
- Inspect for consistency of the concrete mix, including aggregate size and distribution.
- Inspecting for rust stains and discoloration, and physical reduction in cross-sectional area of the reinforcing steel.

3.5 Laboratory Testing

Laboratory analyses were conducted on 48 core samples extracted from the Sasol Secunda site. This was done to identify potential deterioration mechanisms and facilitate the testing of the in-service durability performance of the CTs. The cores were extracted in February 2023, and were transported to the University of Witwatersrand Civil Engineering durability laboratory in Gauteng, Johannesburg for testing. The cores were taken in all quadrants of the tower. This involved 4 cores extracted per level of the tower, namely the upper, middle, and lower levels resulting in 12 cores per quadrant.

3.5.1 Durability index testing

The objective of the Durability Index was to supply an outline for describing the required concrete quality necessary to withstand specific environmental challenges and resist the ingress of aggressive agents. This approach further enables the formulation of predictive models for service life estimation, as outlined by Alexander et al. in 2008.

Once the durability parameters are determined and quantified with respect to the Durability Index, they can be prescribed to establish precise construction specifications, including mix designs tailored to meet the standards necessary for a given application and environment.

The values obtained from these tests may not be entirely representative of the fundamental material characteristics of the original concrete mix, the results will be used to provide indexes which can be used to predict material performance (Otieno et al, 2008).

The DI testing methods were developed to assess early age characteristics of concrete, at an age of 28 – 35 days (Nganga, 2012). The testing of specimens at matured ages reduces the effectiveness of the DI test methods in quality control. Moreover, delayed testing of specimens may result in higher OPI values or lower WSI values as the samples have already been exposed to environmental moisture and have experienced further hydration. (Nganga, 2012).

In order to conduct these tests, 70 ± 2 mm diameter cores are extracted from the designated locations within the test structures. In the case of the Sasol Secunda cooling towers 100 mm cores were extracted from the test structures. Subsequently, the 70 ± 2 mm cores were extracted from the 100 mm core as shown in Figure 3.9 below.

Figure 3-9: 70mm durability specimen extracted from a 100mm core.

These cores are then cut into 30 ± 2 mm thick discs, which serve as the specimens for the DI tests. Detailed procedures for these tests can be found in the Durability Index Testing Manual, as outlined by Alexander et al 2017. The drying process is shown below in Figures 3.10 below where the durability samples are place in the oven and dessicator.

The specimens were placed in the oven as shown and maintained at 50 ± 2°C, for a period of 7 days. Sufficient space was allowed between and around specimens to ensure uniform drying. The specimens were removed from the oven and immediately placed in the desiccator as shown.

Figure 3-10: Durability specimens discs being dried in the oven and dessicator.

3.5.1.1 Water Sorptivity Testing

The Water Sorptivity Index serves as a measurement to measure the rate at which water moves through concrete under the influence of capillary action. This index is an important indicator of concrete's porosity, exhibiting its ability to absorb and transport water. To ensure uniform moisture content, concrete disc samples were exposed to an oven-drying process at 50°C for a duration of seven days or more.

To facilitate unidirectional water movement, the sides of the specimens were sealed using packaging tape. Afterwards, the prepared specimens were placed in a shallow depth of water, and their mass was periodically measured at specific time intervals to ascertain the amount of absorbed water, following the methodology described by Otieno in 2008. The initial weight (M_{so}) of the oven-dried concrete was recorded with accuracy to the nearest 0.01g. The specimens were partially immersed in a solution of distilled water saturated with $Ca(OH)_2$, exposing one face to the solution, as illustrated in Figure 3.11.

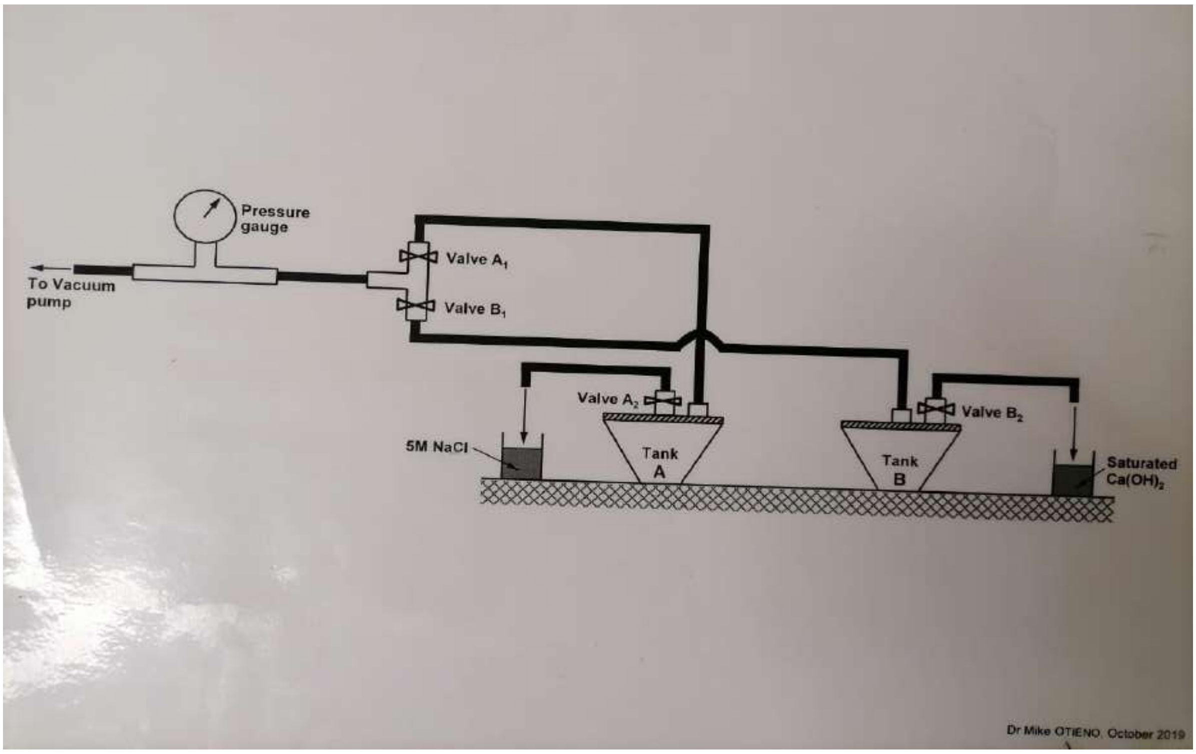

Figure 3-11: WSI Vacuum Saturation Experimental Setup Schematic

The weight of the partially immersed concrete discs (M_{sat}) was accurately measured at intervals of 3, 5, 7, 9, 12, 16, 20, and 25 minutes. The samples underwent vacuum saturation at pressures ranging from −75kPa to −80 kPa for a duration of three hours. The chamber was then filled with the Ca $(OH)_2$ solution to a level of 40 mm above the top of the specimens. The vacuum saturation process was repeated at the same pressures for an additional one hour, plus or minus 15 minutes. The specimens were allowed to soak for an additional 18 hours before being subjected to another round of weighing to achieve the vacuum saturated mass (M_{sv}) of the samples. An image of the experimental procedure is depicted below in Figure 3.12 and 3.13.

Figure 3-12: Water Sorptivity Test being carried out in the laboratory.

Figure 3-13: Vacuum Saturation Process

The experimental setup used during the testing of the specimens is depicted in Figure 3.12. The water sorptivity (S) was determined from the slope of the linear relationship between the mass of absorbed water and the square root of time, as outlined in Equation (1) below:

$$\boldsymbol{S} = \frac{F.d}{(M_{sv} - M_{S0})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3.1)$$

where:

F represents the slope of the best-fit line measured in grams per square root of hour.

D stands for the average specimen thickness, rounded to the nearest 0.02 mm, measured in millimetres (mm).

M_{sv} denotes the vacuum-saturated mass of the specimen, rounded to the nearest 0.01 g, measured in grams.

M_{s0} is the mass of the specimen at the initial time (t_0), rounded to the nearest 0.01 g, measured in grams.

The Water Sorptivity Index values obtained through this experiment provide essential insights into concrete durability. Lower values are indicative of superior potential durability, with typical ranges being 5 mm/√h for grade 30-50 concretes and 15-20 mm/√h for grade 20 concretes (Ballim et al., 2009).

3.5.1.2 Chloride conductivity testing.

The Chloride Conductivity test is an assessment method aimed at characterizing concrete's characteristic capacity to resist chloride penetration, as introduced by Streicher and Alexander in 1999. This test involves the measurement of current across a concrete sample subjected to a 10V potential difference, as illustrated in Figure 3.14.

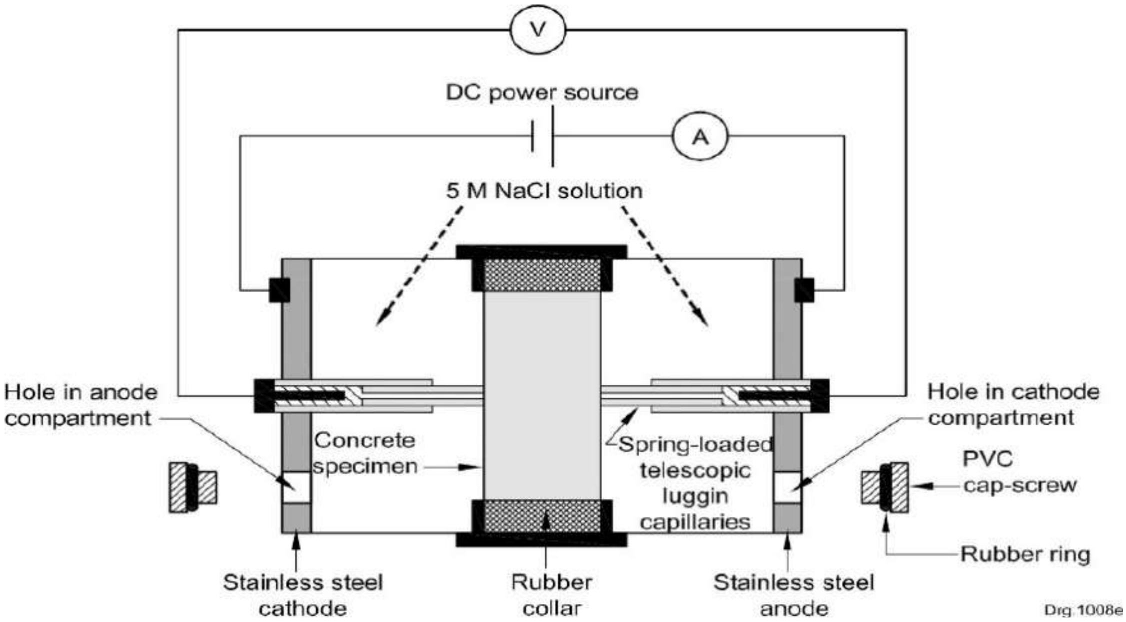

Figure 3-14 : Telescopic Tube Arrangement (Alexander et al, 2023)

To prepare the concrete disc samples, measuring 70 ± 2 mm in diameter and 30 ± 2 mm in thickness, an initial step involves oven drying at 50°C for a duration of seven days. Following this, the specimens undergo vacuum saturation in a 5M NaCl solution for an 18-hour period. Subsequently, the specimens are dried, measured, and placed within the testing rig.

Once securely positioned within the test rig, both the anode and cathode compartments are filled with a NaCl solution through designated openings, ensuring a tight seal to prevent any leakage.

The test commences by connecting and adjusting the ammeter and voltmeter. During the test, simultaneous readings of the electric current (i) and voltage (V) are recorded, as depicted in Figure 3.16. The calculation of the Chloride Conductivity (σ) index value is derived from Equation (2) below:

$$\boldsymbol{\sigma = \frac{id}{VA}} \text{ ....(3.2)}$$

Where:

σ	is the chloride conductivity of the specimen (mS/cm).
I	is the electric current (mA).
D	is the average thickness of the specimen (cm).
V	represents the voltage difference (V).
A	denotes the cross-sectional area of the specimen (cm^2).

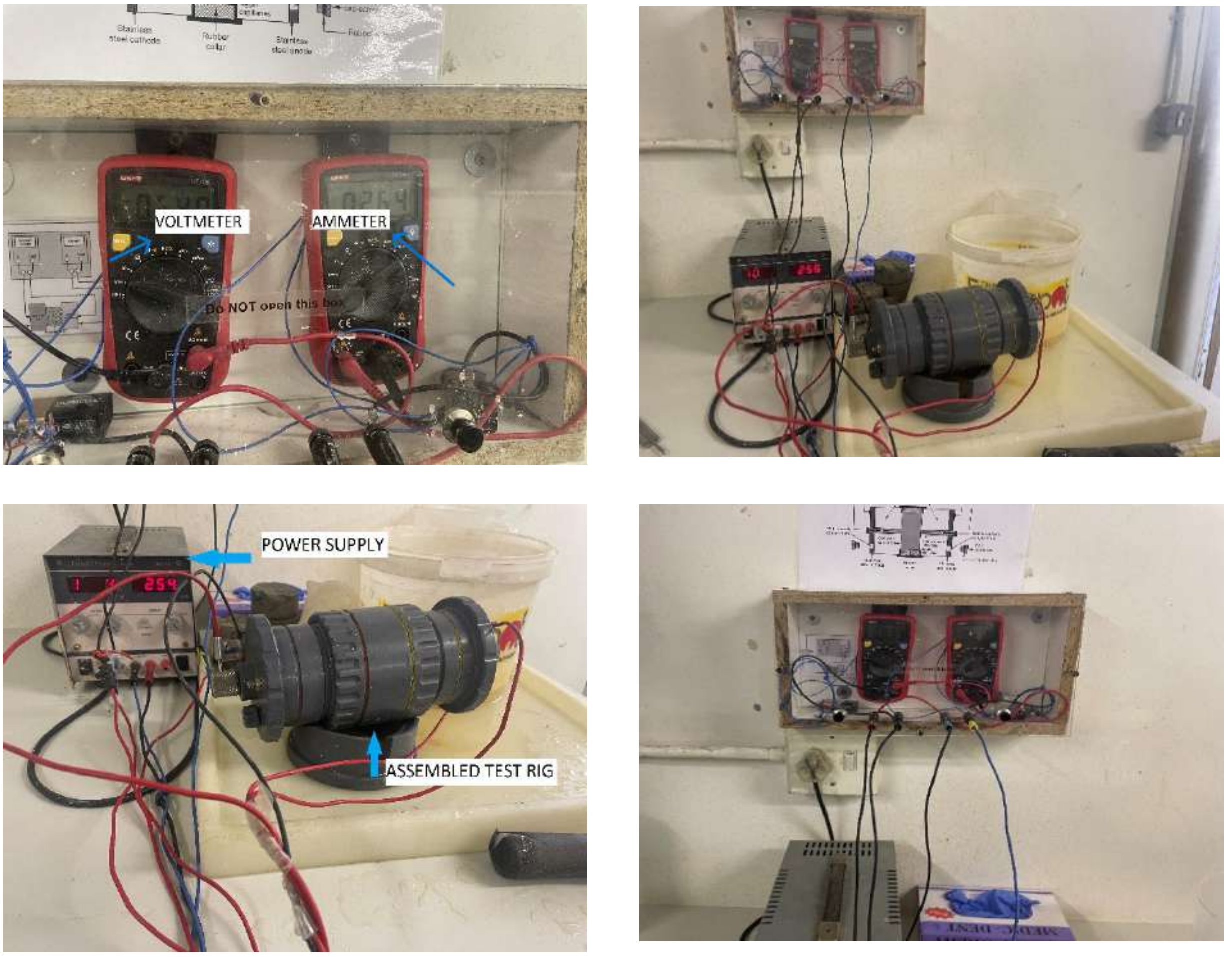

Figure 3-15: Experimental Setup for Chloride Conductivity in the Laboratory

The Chloride Conductivity Index values obtained through this method offer understandings into the concrete's potential durability. Lower values indicate a higher potential for durability, with typical ranges falling between 0.75 and 2.5, as reported by Streicher and Alexander in 1999.

3.5.1.3 Oxygen permeability testing.

The Oxygen Permeability Index test method is used to assess the oxygen permeability characteristics of concrete. This test involves measuring the rate of pressure decline as oxygen passes through a 30 ± 2 mm thick slice of a 70 ± 2 mm diameter concrete core. The governing principle behind this assessment is the Darcy equation, which allows for the determination of he concrete's coefficient of permeability, as proposed by Ballim in 1991.

The apparatus utilized for this test is known as the falling head permeameter, a device developed at the University of Witwatersrand. In this test, an initial pressure is applied to one side of the concrete specimen, while the other side remains at normal atmospheric pressure, as described by Otieno in 2008.

To prepare the concrete disc specimens, they are subjected to an oven-drying process at 50°C for seven days. This specific temperature and duration are selected to minimize microstructural alterations in the specimens while maintaining internal moisture balance, as per the findings of Ikotun in 2017. Following drying, the specimens are cooled in a desiccator for three hours before being positioned within compressible collars and subsequently loaded onto the permeability loading rigs, as depicted in Figure 3.16.

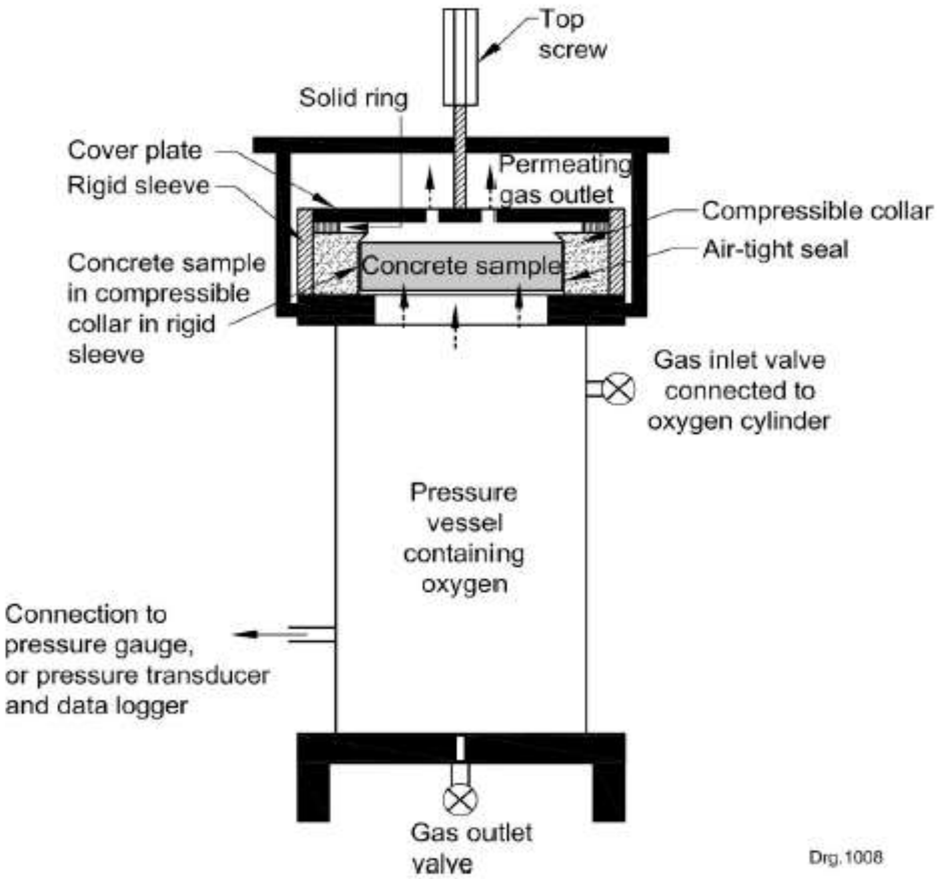

Figure 3-16 : Permeability Cell Arrangement (Alexander et al, 2018)

During the test, as oxygen permeates the specimen, the decrease in pressure with time is carefully monitored. The oxygen permeability coefficient (k) is determined, as specified in Equation (3) (Alexander et al., 2018):

$$k = \frac{\omega * V * g * d * z}{R \; x \; A \; x \; T} \quad \text{.......................}\textbf{(3.3)}$$

Where:

k is the coefficient of permeability of the test specimen in metres per second (m/s).

ω is the molecular mass of oxygen (i.e., 0.032 kg/mol), in kilograms per mole (kg/mol);

V is the volume of the permeability cell, recorded to the nearest 0.01 litre or 0.00001 m^3. The volume of the permeability cell includes the volume of the cell up to the lower face of the specimen. The volume shall be determined by dimensional measurement, accurate to the nearest mm, or by the volume of water contained at 23 ± 2 ºC.

g is the gravitational acceleration (i.e., 9.81 m/s^2), in metres per second squared (m/s^2);

d is the average specimen thickness, to the nearest 0.02 mm, in metres (m);

z is the slope of the linear regression line forced through the (0,0) point, in reciprocal seconds (s^{-1});

R is the universal gas constant (8.313 Nm/Kmol), in newton metres per Kelvin mole (Nm/Kmol).

A is the cross-sectional area of the specimen, in square meters (m^2);

T is the absolute temperature in Kelvin (K).

Figure 3-17 – Samples being inserted into the collar.

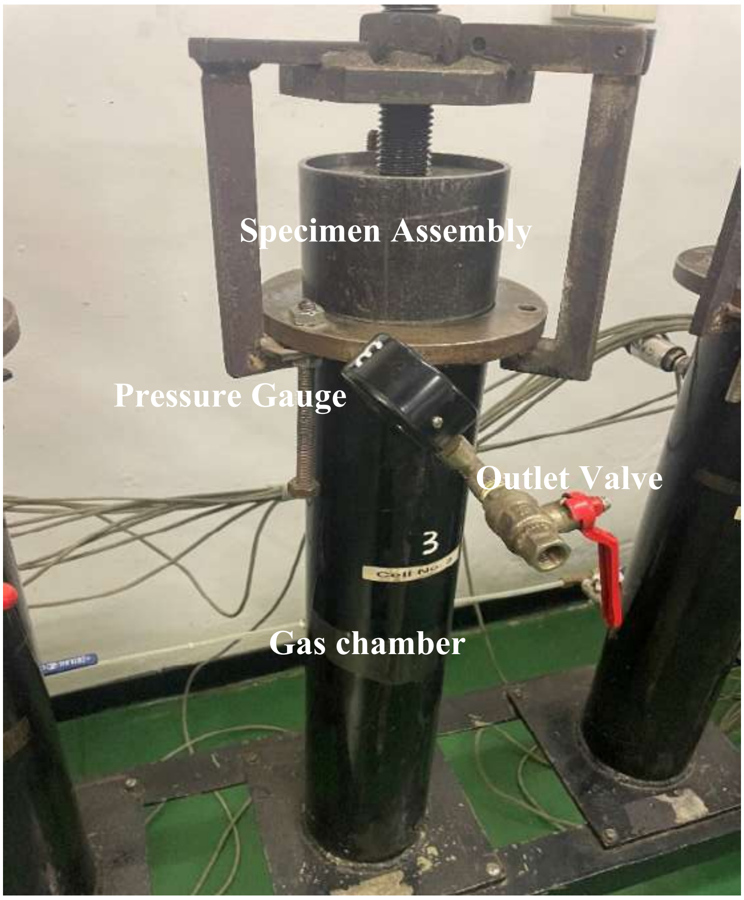

Figure 3-18 – Pressure vessel containing oxygen being pushed through the sample.

The Oxygen Permeability Index (OPI) is calculated by taking the negative logarithm of the oxygen permeability coefficient (k): $OPI = -\log_{10} k$. A higher OPI value means an increased impermeability, which is an indicator of superior-quality concrete. Typically, OPI values fall within the range of 8.5 to 10.5.

3.5.1.4 Limitation of DI Tests on cracked samples

The durability test methods and apparatus were developed with consideration and emphasis placed on ensuring that the concrete specimen is not extracted from an area that contains cracks. Extreme care needs to be taken during the coring and cutting of the specimen. This is done in order to ensure no further damage to the specimen occurs before testing.

The limitation with this testing method is that it only focuses on sound concrete for testing (Kanjee, 2015). Regardless of whether the structure exhibits signs of cracking on the surface, this area of concrete cannot be used for testing Figure 3.19 below indicates a cracked sample being inserted to the collar that was rejected for testing.

Figure 3-19: Cracked specimen inside the collar rig.

When sound concrete specimens are tested, a higher OPI value is obtained. This shows a high degree of impermeability of the concrete. On the contrary, when a cracked concrete specimen is tested, a low OPI value is obtained. This indicates a high degree of permeability in comparison to the sound concrete specimen. The presence of cracks creates a passage for gas to permeate through the concrete pore structure, signifying that the concrete has high degree of permeability.

When the sound concrete and the crack concrete specimen OPI values are used for service life modelling and prediction, they characterise two extreme scenarios. In the case of the sound concrete, the high OPI value will indicate that hardly any permeation will take place. In the cracked concrete specimen, the low OPI value will indicate that severe permeation will take place in the cracked areas (Kanjee, 2015).

3.6 Water Chemistry Analysis

The water chemistry dataset sourced from the Sasol laboratory underwent an examination to determine the concentrations of ionic species in the water. This analysis was conducted in conjunction with the evaluation of the Basson corrosion index, a system designed to estimate the water's tendency to leach calcium from concrete (Basson, 1989). The index also considers the potential for other aggressive ions existing in the water to initiate harmful reactions with the concrete.

Calcium compounds play a fundamental role in hydrated cement paste and influence the performance of concrete considerably. Among these compounds, two specific categories are of particular relevance concerning calcium leaching: the calcium hydroxide phase and the calcium-silicate-hydrate gel (C-S-H).

The calcium hydroxide phase informs higher alkalinity to the concrete, thus enhancing its resistance to the corrosion of reinforcing steel. When concrete is exposed to water, calcium hydroxide dissolves and forms a highly alkaline solution. This alkaline environment leads to the formation of a thin, passive layer of iron oxide on the surface of the steel reinforcement bars embedded in the concrete. This passive layer acts as a barrier, preventing the steel from coming into direct contact with oxygen, water, and other corrosive agents. This process, known as passivation, significantly slows down the rate of corrosion and prolongs the lifespan of the steel reinforcement (Mehta et al 2014).

Additionally, the calcium-silicate-hydrate gel (C-S-H) is fundamental to providing concrete with its structural strength (Basson & Addis, 1992). Both these calcium compounds are essential elements, and their susceptibility to leaching must be considered when assessing the durability of concrete structures.

Cooling tower concrete is continuously exposed to aggressive water and a humid environment, which can lead to leaching of calcium hydroxide and a reduction in the alkalinity of the concrete. Cooling towers in a petrochemical environment are often exposed to acidic pollutants in the air, which can further accelerate the carbonation process (reaction of CO_2 with calcium hydroxide). This can compromise the protective layer on the steel reinforcement and increase the risk of corrosion.

3.6.1 Basson Corrosion Indices

The Basson corrosion index serves as a valuable tool for assessing the tendency of water to interact aggressively with concrete, possibly leading to leaching and spalling of the concrete structure. These indices include two sub-indices: the leaching corrosion sub-index (LCSI) and the spalling corrosion sub-index (SCSI). Combining these two sub-indices, an overall corrosion index (OCI) is derived called the Aggressiveness index (AI), offering a complete evaluation of the water's corrosiveness. The development of these indices is rooted in empirical data gathered from field observations conducted by Basson and Addis. To enable practical analysis, the values are normalized, with values exceeding 1000 indicative of water that is "very highly aggressive" toward concrete, as established by Basson and Addis in 1992.

These corrosion indices offer means of evaluating the aggressiveness of various ions present in water sources. The specific components of these indices:

1. ***Leaching Corrosion Sub-index (LCSI):***
    - The LCSI assesses the water's potential to leach calcium from the concrete.
    - A positive LCSI value indicates the potential for calcium leaching from the concrete, while a negative value suggests the possibility of calcium deposition.
2. ***Spalling Corrosion Sub-index (SCSI):***

- The SCSI focuses on the water's ability to induce spalling on the concrete surface.
- This sub-index is affected by the concentrations of dissolved salts, particularly those known to cause concrete spalling. Particularly, salts containing magnesium, ammonium, and sulphate ions are considered.
- Ammonium ions are agreed to have greater significance in the calculation due to their increased aggressiveness toward concrete compared to magnesium and sulphate ions.

The evaluation of the Basson corrosion indices, in the context of process cooling water chemistry data, provides helpful insights into the potential effects of the water on concrete structures. This assessment helps making informed decisions regarding concrete composition, protective measures, and maintenance strategies to mitigate the corrosive impact of the water source.

3.7 Chapter Summary and Closure

The methodology chapter of this research provides a comprehensive framework for assessing the in-service durability performance of natural draft cooling towers in a petrochemical environment. The study focuses on the Sasol Secunda Natural Draft Process Water Cooling Tower, which has been in operation since the early 1980s and has experienced varying degrees of concrete deterioration due to the nature of its aggressive environement and exposure to aggressive waters.

The methodology involves a multi-faceted approach, combining historical data analysis, field investigations, and laboratory testing. Historical data, including structural information, and environmental data, was collected to understand the tower's construction, operational history, and environmental context. This data provides a baseline for assessing the tower's current condition and identifying potential deterioration mechanisms.

Field investigations were conducted to assess the tower's current state. Visual inspections from ground level and hands-on surveys of the tower's exterior surface were performed to identify visible signs of deterioration, such as cracking, spalling, erosion and discoloration. Non-destructive testing (NDT) techniques, such as the cover meter survey using Ground Penetrating Radar (GPR), were employed to measure the depth of concrete cover over the reinforcing steel. This information is crucial for evaluating the level of protection against aggressive agents and assessing the risk of corrosion.

Laboratory testing was a central component of the methodology. Core samples were extracted from various locations and elevations on the cooling tower shell. These cores were then subjected to durability index testing, including the Water Sorptivity Index (WSI), Chloride Conductivity Index (CCI), and Oxygen Permeability Index (OPI) tests. These tests assessed the concrete's resistance to water absorption, chloride ion penetration, and oxygen permeability, respectively. Additionally, water chemistry analysis was performed to determine the concentrations of ionic species in the cooling water and evaluate its aggressiveness towards concrete using the Basson corrosion index.

The next chapter will cover the results and discussions derived from the experimental investigations outlined in this chapter.

4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results obtained from the on-site and laboratory investigations, as outlined in Chapter 3. The primary focus is to evaluate the in-service durability performance of the Sasol Secunda Natural Draft Cooling Tower, particularly in the context of its exposure to a harsh petrochemical environment. The analysis includes interpreting the Durability Index (DI) test results to understand the potential relationship between the environment and the structural integrity of the cooling towers. Additionally, potential deterioration mechanisms affecting the cooling tower are explored, drawing insights from visual observations, non-destructive testing (NDT) data, and experimental data.

The chapter begins with a systematic documentation of the visual and NDT assessment of the cooling tower, indicating the location and extent of deterioration. This is followed by a detailed presentation of the core log information, including observations and photographs, to provide a comprehensive understanding of the core samples' condition. The laboratory testing results, including the durability index tests (water sorptivity, chloride conductivity, and oxygen permeability), are then presented and analyzed. The water chemistry results are also discussed, focusing on their relevance to the water in contact with the tower's surface.

By integrating the findings from visual assessments, NDT data, core log information, and laboratory testing, this chapter aims to provide a holistic evaluation of the in-service durability performance of the Sasol Secunda Natural Draft Cooling Tower. The results and discussion presented in this chapter will contribute to identifying the primary deterioration mechanisms and understanding the factors influencing the durability of cooling towers in harsh petrochemical environments.

4.1.1 Visual Assessment Findings

A comprehensive visual assessment of the cooling tower was conducted, focusing on identifying and documenting the types, extent, and location of deterioration. The assessment covered the entire exterior shell of the tower, utilizing both ground-level observations and hands-on surveys conducted from temporary suspended platforms (TSPs). The visual assessment was supplemented with hammer sounding to detect subsurface delamination and a cover meter survey to measure the depth of concrete cover over the reinforcing steel. In the investigation of the cooling tower, concrete deterioration was a prevalent issue, manifesting as cracking, delamination, and spalling across the tower's shell surface. These defects are often associated with the corrosion of embedded reinforcing steel, as evidenced by surface discoloration, cracking, spalling and surface erosion, which, in turn, expose the steel to environmental factors, accelerating the corrosion process. This section discusses the observed cracking and spalling in the cooling tower structure within the context of a petrochemical environment.

These defects were not uniformly distributed across the tower but were predominantly concentrated in the upper sections. The lower levels of the tower exhibited less pronounced deterioration. A detailed mapping of the observed defects, indicating their location and severity, is presented in Table 4.1.

Table 4-1 Detailed mapping of observed defects

Tower Height (m)	***Quadrant 1***	***Quadrant 2***	***Quadrant 3***	***Quadrant 4***
11	C,S	-	-	C
19	C,D	C	D	C
30	E	C	E	C
41	D	C	C	C
56	-	S,E	D	S,E
65	S,E	S,E	S,E	S,E
77	S,E	S,E	S,E	S,E
90	S,E	S,E	S,E	C,S,E
100	C,S,E	C,S,E	E	E
104	C,S,E	S,E	C,S,E	C,S,E

Note: C = Cracking, D = Delamination, S = Spalling, E = Erosion

The observed concentration of concrete defects (cracking, spalling) was predominantly located in the upper sections of the cooling tower. This phenomenon can be attributed to several interacting factors. Firstly, the elevated position of these sections increases their exposure to airborne contaminants and process water vapor, exacerbated by prevailing winds. The resultant chemical reactions degrade the concrete matrix, promoting structural weakness. Secondly, thermal cycling due to operational processes induces stress, further contributing to cracking and spalling. Additionally, evaporative cooling leads to increased moisture levels at the top, facilitating corrosion of the steel reinforcement and subsequent concrete deterioration. The elevated wind speeds typical of petrochemical facility locales (SANS 10160-3:2019) further exacerbate these degradation mechanisms.

The design of natural draft cooling towers inherently creates a thermal gradient, with the highest air temperatures at the top due to heat extraction from the water. This warmer, moist air is less dense and naturally rises, creating the upward draft that drives the cooling process. This, combined with high moisture levels, can accelerate corrosion of embedded steel reinforcements. Corrosion products expand, leading to concrete spalling (Dhawan et al., 2019).

Beyond cracking and spalling, visual assessment revealed areas of softened concrete, surface erosion, and exposed aggregate (Figure 4.1). This erosion of the cement paste matrix is indicative of advanced deterioration and exposes the concrete to further degradation. The variability in concrete condition, even within the same lift level, suggests potential inconsistencies in material properties, construction practices, or localized exposure to aggressive environmental factors.

Figure 4-1: Exposed aggregate due to erosion of cement paste (Gries et al, 2022)

Visual inspection of the upper level of the cooling tower revealed evidence of cement paste erosion. This manifests as exposed aggregate, a clear indication of deterioration within the concrete matrix. Figure 4.2 further highlights the concerning variability in concrete condition across the tower height and circumference. Notably, even within the same lift level (lift 99 and 100 for quarter 2), adjacent concrete sections exhibited visible differences in quality.

These observations suggest a potential combination of factors contributing to the observed deterioration. The localization of severe erosion at the upper level aligns with the view of increased exposure to aggressive chemicals such as chlorides and sulfates, temperature fluctuations, and moisture accumulation discussed previously. The significant variation in concrete quality, even within close proximity, could be attributed to inconsistencies in material properties, construction practices, or the presence of localized aggressive agents within the process water in the cooling tower. The water chemistry is discussed later in ths chapter.

Figure 4-2: Varying concrete conditions at different locations of the tower

The laboartory analysis also identified a considerable number of cores from the upper level exhibiting notably poor concrete quality discussed in the subsequent sections. This variability suggests potential inconsistencies in the original concrete mix design, material properties, or construction practices during those specific lift levels. Such inconsistencies could lead to weaker concrete sections more susceptible to deterioration under harsh exposure conditions.

The condition of the reinforcing steel varied across the tower. While minor corrosion was observed on some bars throughout the structure where there were open repair patches, the upper levels again displayed a concerning trend. Bars located at these lift levels exhibited more pronounced signs of corrosion, often positioned adjacent to visible concrete cracks. This suggests a potential link between the observed cracking, facilitating the ingress of aggressive agents like chlorides from the surrounding environment and cooling water, and the initiation and progression of steel corrosion.

4.1.2 Ground Penetrating Radar (GPR) Cover Meter Survey Findings

Cover meter surveys were conducted along the height of the tower where defects were visible. The results are documented below and used to correlate the various cover depths along the height of the CTs to the defects visually identified on the tower. The deductions from the correlation will be used to characterize possible corrosion mechanisms responsible for the defects identified.

The design cover depth for this cooling tower was 40mm. The changes and variations with the cover depth shown in Figure 4.3 could possibly be due to poor construction practices at the time of construction. Concrete sections with insufficient cover and deteriorated concrete, as indicated by the variations in Figure 4.3, are susceptible to easier penetration by aggressive agents such as chlorides and sulfates in the operating environment. This compromises the passive protective layer of the reinforcing steel, leading to accelerated corrosion of the reinforcing steel and subsequent deterioration of the concrete structure (Beuhausen et al., 2021).

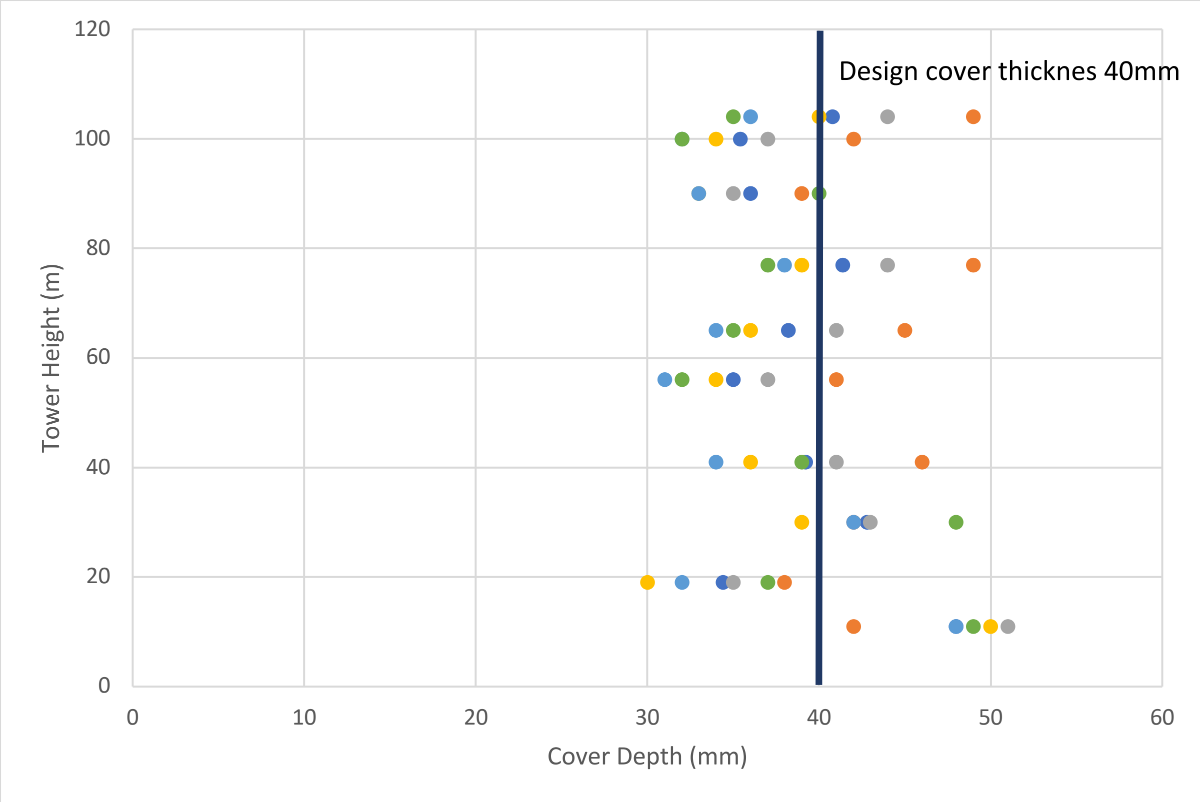

Figure 4-3 Cover Depth Measurements from cooling tower shell exterior

Cover meter readings identified concerning discrepancies between the measured cover depth and the specified design value of 40 mm for the reinforcing steel within the cooling tower shell. This inadequate concrete cover significantly increases the risk of compromised durability and insufficient protection against aggressive agents. These agents, such as chlorides and sulfates commonly found in petrochemical environments (Ropital, 2009), can accelerate concrete deterioration and trigger corrosion of the embedded steel reinforcement.

The analysis of cover meter data from the Sasol Secunda cooling tower reveals a concerning trend: the concrete cover depth, designed to be 40 mm, is consistently less than this standard at all measured elevations except 11 meters shown in Table 4.2. This deviation is substantial and suggests potential flaws in the construction process, particularly in concrete placement and consolidation. It is also possible that some of the cover concrete has been lost due to erosion or deterioration by spalling, cracking or delamination.

Table 4-2 Cover reading data recorded at different tower heights

Tower Height	*Reading 1*	*Reading 2*	*Reading 3*	*Reading 4*	*Reading 5*	*Average*	*SD*	*CoV (%)*
11	49	48	50	51	42	48	3.16	6.59
19	37	32	30	35	38	34.4	3.01	8.74
30	48	42	39	43	42	42.8	2.93	6.84
41	39	34	36	41	46	39.2	4.17	10.63
56	32	31	34	37	41	35	3.63	10.38
65	35	34	36	41	45	38.2	4.17	10.91
77	37	38	39	44	49	41.4	4.50	10.87
90	40	33	33	35	39	36	2.97	8.24
100	32	32	34	37	42	35.4	3.77	10.66
104	35	36	40	44	49	40.8	5.19	12.73

**5 readings were taken at each of the above heights*

Areas with insuffient concrete cover and deteriorated concrete significantly increase the vulnerability of reinforced concrete structures to the ingress of aggressive agents, accelerating the corrosion process. The thickness and quality of the concrete cover directly influence the transport of moisture and gases, which are critical factors in the initiation phase of the corrosion process as illustrated in Figure 2-6 (Chapter 2). Compromised concrete quality expedites this phase, leading to premature corrosion onset. This is further evidenced by visual inspection findings of spalling, discoloration, and softened cement paste, all indicative of advanced concrete degradation and potential corrosion of embedded steel reinforcement.

4.2 Core extraction results

4.2.1 Description of cores extracted

Cores were extracted in all four quarters of the tower and at various heights as discussed in Chapter 3. The significance of dividing the Cooling tower into four quarters offers a strategic approach to understanding how the varying exposure conditions contribute to the observed deterioration of the cooling tower surface. Examining all four quadrants allows for a comparative assessment of the concrete's overall condition. The upper areas of the tower are likely to be exposed to higher concentrations of aggressive chemicals present in the process water vapor and potentially experience greater temperature fluctuations. This can lead to more advanced deterioration compared to lower sections.

General visual observations of all the cores revealed some notable findings but in general the quality and condition of the extracted cores was acceptable for testing. The cores exhibited signs of slight discoloration, hairline cracking and visible cracking around the aggregates. The number of transverse and longitudinal cracking were significantly higher on the cores extracted from the upper levels of the tower. The void content observed seemed adequate and adequately distributed across the cross-sectional area of the cores. Spatial distribution of the aggregates of the cores was relatively good and, in some instances, larger than usual aggregates were found.

Detailed core log can be found in Appendix A1.

4.3 Laboratory testing results

This research study sought to evaluate the in-service durability performance of the Sasol Secunda Natural Draft Cooling Towers through the implementation of the Durability Index (DI) tests. This included the analysis of extracted concrete core specimens that were tested using the procedures stipulated in the the relevant SANS codes and DI Manual. The DI test specimens were prepared in accordance with SANS 3001: CO3-1. The oxygen permeability index (OPI) test was conducted according to SANS:3001-CO3-2. The water sorptivity test was conducted in accordance with the Durability Index Manual. The chloride conductivity test was conducted according to SANS:3001-CO3-3.

Specifically, the Oxygen Permeability Index (OPI), Water Sorptivity Index (WSI), and Chloride Conductivity Index (CCI) tests were employed to assess the material's resistance to oxygen permeability, water ingress, and chloride ion penetration, respectively.

4.3.1 Durability testing

The Durability Index tests assessed the various transport mechanisms within the concrete samples to evaluate its in-service durability performance.

4.3.1.1 Water Sorptivity Results

The Water Sorptivity Index serves as a measurement to measure the rate at which water moves through concrete under the influence of capillary action. This index is an important indicator of concrete's porosity, exhibiting its ability to absorb and transport water.

Concrete's resistance to moisture penetration is increased with lower sorptivity values. The sorptivity values presented in Table 4.3 range from 7.02 mm/hr^0.5 to 22.19 mm/hr^0.5, indicating a variation in the concrete's initial water absorption rate. It isimportant to remember that specific WSI thresholds for acceptable performance depend on the application and exposure conditions. The higher WSI values indicate an increased susceptibility to moisture ingress in the Cooling Tower.

Table 4-3: Tower Water Sorptivity Index Results

Tower Bottom	***Core Location***	***Sorptivity (mm/hr^0.5)***	***Porosity (%)***
Q2	L16B	22.19	10.21
Q3	L13M	22.09	9.48
Q3	L16B	15.34	9.57
Q4	L15B	13.02	8.36
Tower Middle	***Core Location***	***Sorptivity (mm/hr^0.5)***	***Porosity (%)***
Q1	L34B	15.51	7.67
Q2	L38M	10.9	9.35
Q3	L31B	11.82	8.66
Q4	L32F	7.02	9.42
Tower Top	***Core Location***	***Sorptivity (mm/hr^0.5)***	***Porosity (%)***
Q3	L68F	10.14	16.95
Q3	L68M	7.41	15.42
Q3	L69M	12.91	13.65
Q4	L68F	12.68	14.69
Q4	L68B	8.93	15.54
Q4	L70B	13.02	13.8
Q4	L71M	11.13	16.97

**B = Back, M = Middle, F = Front disc of core*

	Bottom	***Middle***	***Top***
Mean	18.16	11.3	10.9

SD	4.69	3	2.1
Min	13.02	7.02	7.41
Max	22.19	15.51	13.02
CoV (%)	40.28	26.55	19.27

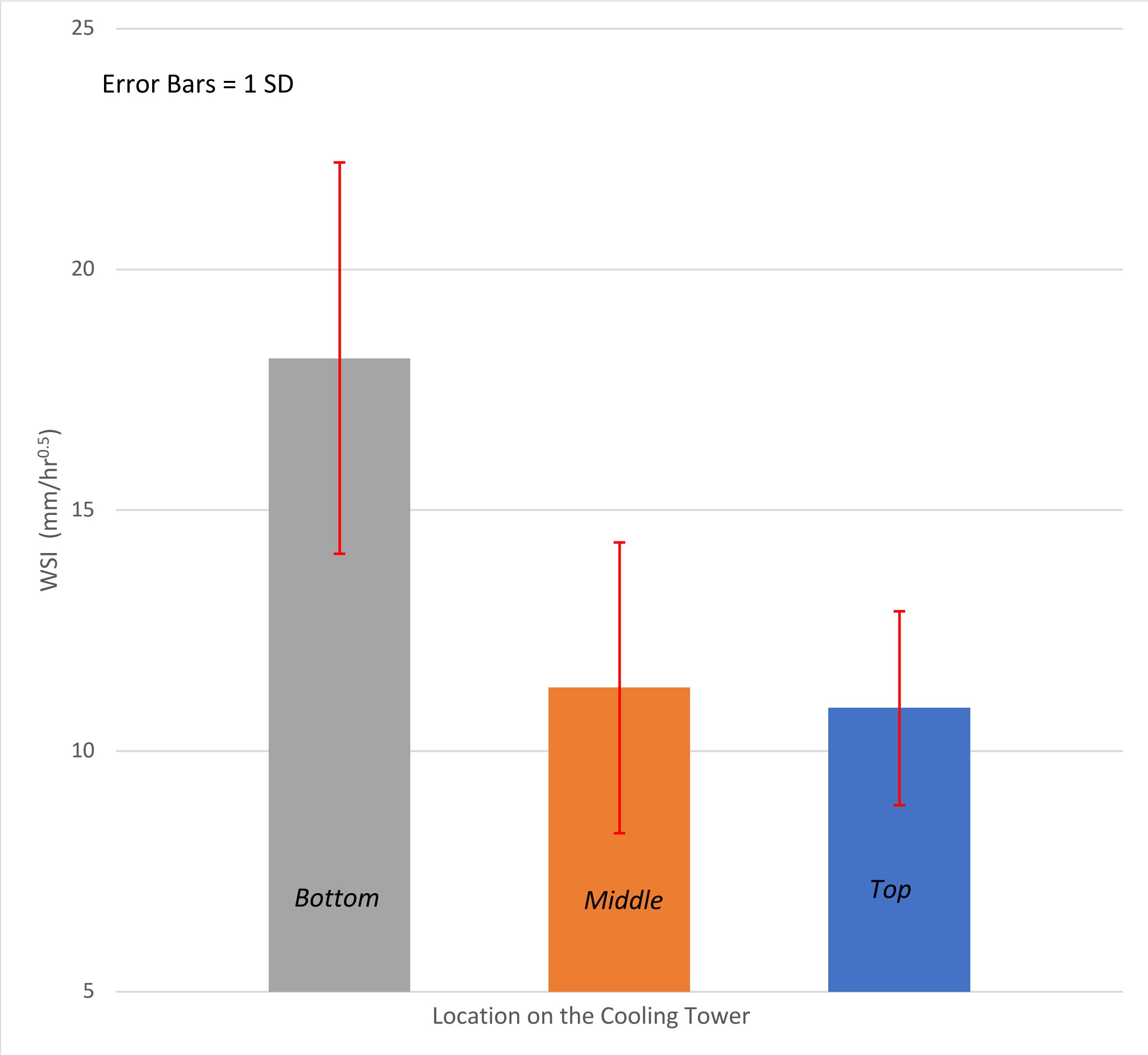

Figure 4-4 - Water Sorptivity results of the samples extracted from the Cooling Tower.

Porosity is a bulk material property, representing the total volume of voids (air pockets) within a concrete sample shown in figure 4.5. These voids can potentially be filled by a liquid, typically expressed as a percentage of the entire concrete volume. In contrast, sorptivity is a near-surface property. It reflects the concrete's ability to absorb a liquid at the surface, influenced by the size and connectivity of pores near the surface, not the total void volume throughout the material (Nganga, 2012).

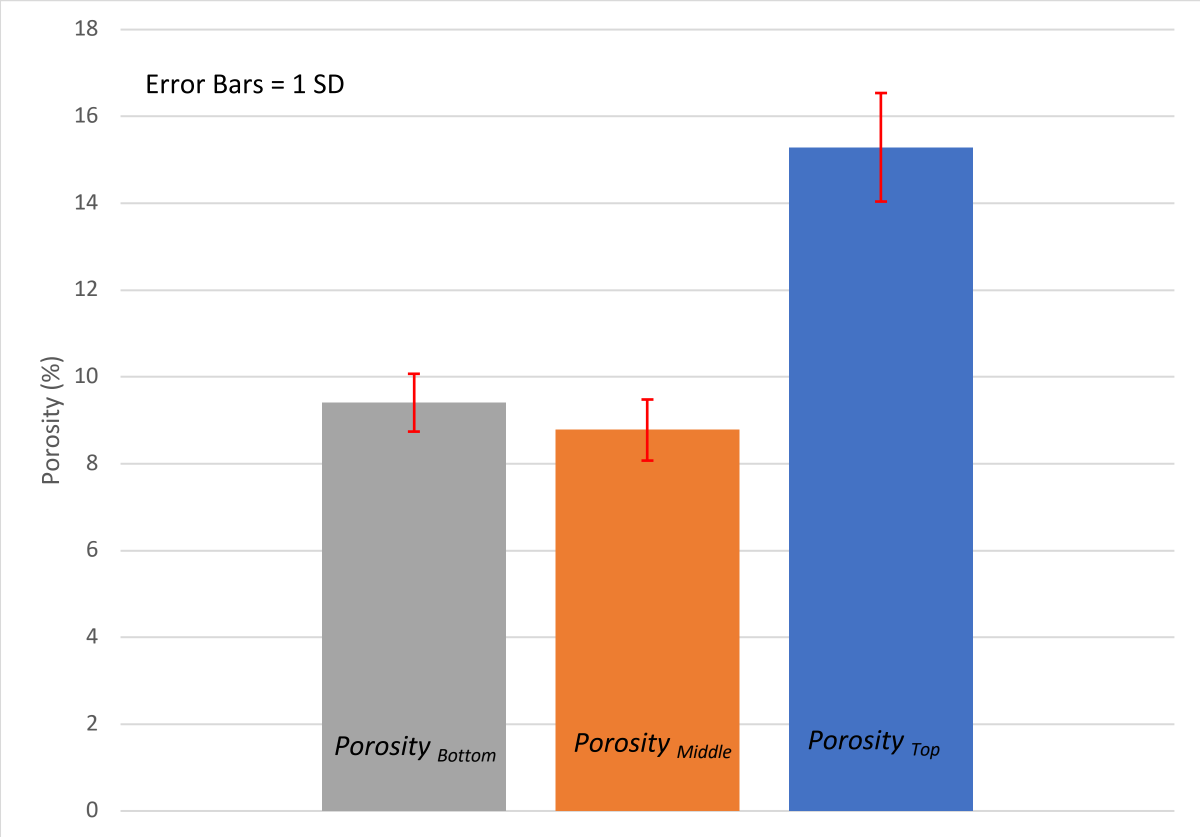

Figure 4-5 - Assosiated Porosity values from Water Sorptivity test

A trend is seen when considering tower elevation. The top sections (L68-L71) exhibited the lowest mean WSI values (around 10.8 mm/hr$^{\wedge 0.5}$) compared to the middle (L31-L34) and bottom sections (L13-L16) with mean values around 11.3 mm/hr$^{\wedge 0.5}$ and 18.2 mm/hr$^{\wedge 0.5}$, respectively. This suggests that the upper concrete levels might have a denser microstructure with a slower initial water absorption rate compared to the other elevations, however the porosity values in the upper sections are higher than both the middle and bottoms sections signifying a close correlation between sorptivity and porosity.

The study on the Sasol Secunda cooling tower provides evidence of the impact of porosity and sorptivity on durability. The results showed a correlation between porosity and the Water Sorptivity Index (WSI), indicating that higher porosity generally leads to increased moisture absorption. While the upper sections of the tower exhibited lower WSI values, their higher porosity suggests a greater susceptibility to deterioration due to the aggressive environmental conditions.

This correlation suggests a connection between the interconnected pore structure and the ease of water uptake. It’s important to acknowledge that factors other than just porosity can influence WSI, such as pore size distribution and connectivity. The observed discrepancy between porosity and sorptivity in the upper sections suggests that the pore structure in these sections may be different from that in the lower sections. The pores in the upper sections may be larger but less interconnected, leading to lower sorptivity despite higher porosity. This could be due to differences in the concrete mix design or curing conditions at different elevations during construction.

The visual inspection identified signs of deterioration throughout the cooling tower structure, including discoloration, cracking, spalling, and delamination. This observed deterioration initially appears to contradict the WSI (Water Sorptivity Index) results, where the upper sections have a lower mean WSI compared to the middle and bottom sections. Traditionally, a higher WSI would be expected to correlate with a higher likelihood of deterioration due to increased water absorption. However, the higher porosity in the upper sections, as indicated by the porosity results, could explain the observed deterioration. The larger pores in these sections may allow for easier ingress of aggressive agents, such as chlorides and sulfates, leading to accelerated deterioration despite the lower initial water absorption rate.

4.3.1.2 Chloride conductivity results

The Chloride Conductivity Index (CCI) reflects both the concrete's resistance to the movement of charged ions under an electrical potential gradient and its susceptibility to chloride ingress by diffusion.

The chloride conductivity test was carried out to assess the concrete's resistance to chloride ingress. This test measures the electrical current passing through concrete samples and translates it into an equivalent Chloride Conductivity Index (CCI) value. Lower CCI values indicate a higher resistance to ionic movement, particularly chlorides, within the concrete. Conversely, higher CCI values signify a reduced ability of the concrete to impede chloride ion transport (Mackechnie, 1996). The Chloride Conductivity values presented in Table 4.4 range from 0.22 to 2.9 mS/cm, with a significant variation observed across the samples.

Table 4-4: Tower Chloride Conductivity Index Results

Tower Bottom	***Core Location***	***Conductivity (mS/cm)***
Q1	L13F	0.42
Q1	L15F	1.06
Q2	L13B	0.47
Q2	L16M	0.34
Q3	L14F	0.51
Q3	L16M	0.47
Q4	L14M	0.25
Q4	L16B	0.6
Tower Middle	***Core Location***	***Conductivity (mS/cm)***
Q1	L34F	0.27
Q1	L35M	0.74
Q2	L39F	0.63
Q2	L39B	0.5
Q3	L30B	0.24
Q3	L30F	0.47
Q4	L33F	0.8
Q4	L33B	0.22
Tower Top	***Core Location***	***Conductivity (mS/cm)***
Q1	L77F	2.47
Q1	L75F	2.46
Q2	L100F	1.78
Q2	L102F	2.54
Q3	L 69F	2.04
Q3	L 69B	2.9
Q4	L71F	1.57
Q4	L70F	1.68

**B = Back, M = Middle, F = Front disc of core*

	Bottom	***Middle***	***Top***
Mean	0.57	0.54	2.18
SD	0.29	0.18	0.45
Min	0.25	0.22	1.57
Max	1.06	0.8	2.9
CoV (%)	50.88	33.33	20.64

Figure 4.6 show the chloride conductivity values and their variability across the different quadrants and heights of the cooling tower.

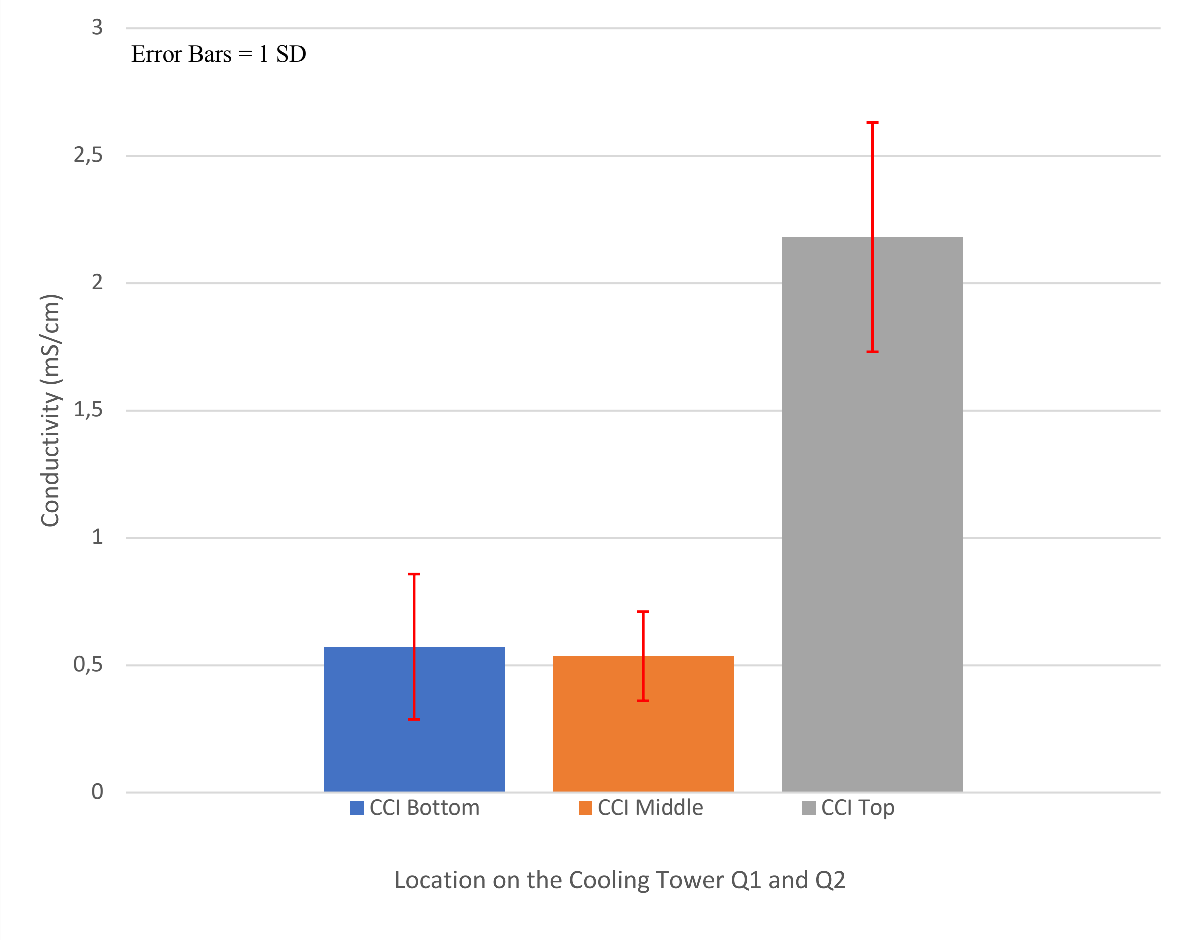

Figure 4-6 Chloride Conductivity results on the samples extracted from the Cooling Tower.

As can be seen, a trend emerged when considering tower elevations. The top sections (L70-L102) exhibited significantly higher mean CCI values (around 2.18 mS/cm) compared to the middle (L30-L39) and bottom sections (L13-L16) with mean values around 0.5 mS/cm. This suggests that the upper concrete layers might be more susceptible to chloride ingress, potentially due to factors like increased exposure to process water vapor and higher chloride concentrations. While the overall trend pointed towards higher CCI values at the top, variations were also observed between quadrants within each elevation. For example, in the top section, quadrants Q1 and Q2 displayed slightly lower mean CCI values compared to Q3 and Q4. These quadrant-specific variations could be attributed to potential differences in exposure conditions, such as the different wind actions across the tower's surface including variations in wind exposure or prevailing wind direction. This could influence the rate of ion accumulation on different quadrants of the cooling tower.

The observed variability in Chloride Conductivity Index (CCI) values across the cooling tower can be attributed to several contributing factors, including poor construction practices such as inadequate compaction, especially during casting of concrete at higher levels with sliding formwork, can lead to trapped air voids and a more porous concrete matrix. This increases the interconnected pathways for chloride ions to move through the concrete, potentially resulting in higher CCI values in those areas. Without access to the original design mix data, definitively pinpointing the exact cause of the CCI variability is currently not possible. However, further investigation and analysis, potentially including petrographic analysis and contamination testing, would help explain the factors contributing to the observed variation in the different quadrants.

The observed trend of increased spalling and delamination in the upper levels, combined with high Chloride Concentration Index (CCI) values, suggests a potential relationship between harsher exposure conditions and material properties. This pattern could be attributed to harsher environmental factors at the upper levels and indicate localized deficiencies in the concrete quality in these specific areas.

4.3.1.3 Oxygen permeability results

The Oxygen Permeability Index (OPI) is defined as the negative logarithm of the oxygen permeability coefficient k (m/s) measured through a concrete sample. It is derived by taking the negative logarithm of the average permeability coefficient obtained from test specimens. While the OPI offers a relative comparison of permeability, the permeability coefficient k (m/s) directly quantifies the concrete's resistance to gas diffusion, providing a more accurate measure of its permeability (Otieno et al 2008). k and corresponding OPI values can be found in Table 4.5 below:

Table 4-5: Tower Oxygen Permeability Index Results

Tower Top	***Core Location***	***OPI:***	***k (m/s)***
Q3	L68F	8.65	2.25E-09
Q4	L71M	8.66	2.18E-09
Q4	L68F	8.96	1.09E-09
Q3	L69M	8.45	3.55E-09
Tower Middle	***Core Location***	***OPI:***	***k (m/s)***
Q1	L34B	8.66	2.17E-09
Q1	L34F	8.67	2.15E-09
Q2	L38M	9.25	5.68E-10
Q2	L38B	9.48	3.30E-10
Q3	L31F	8.71	1.95E-09
Q3	L31B	9.18	6.68E-10
Q4	L32B	8.84	1.43E-09
Q4	L32F	8.68	2.07E-09
Tower Bottom	***Core Location***	***OPI:***	***k (m/s)***
Q2	L16B	8.75	1.79E-09
Q1	L12F	8.75	1.76E-09
Q1	L13B	9.41	3.87E-10
Q1	L15B	8.73	1.85E-09
Q4	L15F	9	9.92E-10
Q4	L15B	9.43	3.71E-10
Q3	L28M	9.84	1.45E-10
Q3	L29F	8.66	2.17E-09

**B = Back, M = Middle, F = Front disc of core*

	Top	***Middle***	***Bottom***
Mean	8.68	8.94	9.11
SD	0.22	0.31	0.46
Min	8.45	8.66	8.66
Max	8.96	9.48	9.84
CoV (%)	2.53	3.47	5.05

Figure 4.7 show the statistical spread of the OPI values for the different quarter and heights of the cooling tower.

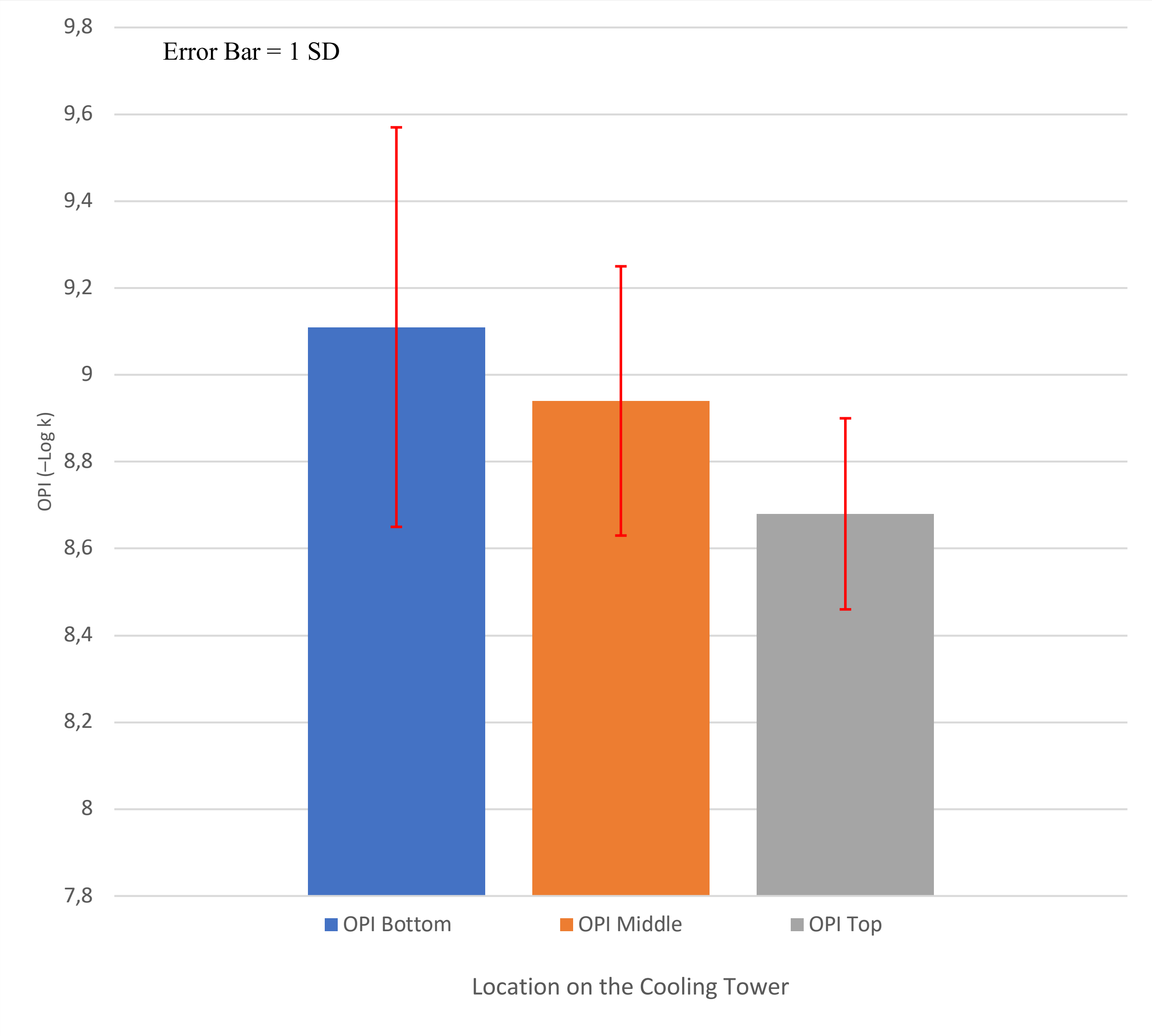

Figure 4-7 Oxygen Permeability results on the samples extracted from the Cooling Tower.

Important to note is the exclusion of OPI results for the top section of the Cooling Tower for quarter 1 and 2. All specimens from the top section for those quarters were not suitable to be tested. These specimens were either cracked and easily damaged during the sample preparation and rejected from the sampling pool.

The OPI values presented in Table 4.5 range from 8.45 to 9.48. The OPI values exhibited relatively small variations between the tower's top, middle, and bottom sections. The mean OPI for each section ranged from 8.65 (Top) to 9.02 (Middle), with standard deviations below 0.4 in all cases. This suggests that the concrete's resistance to oxygen ingress remains fairly consistent throughout the tower's height. While the overall variation across elevations was minimal, a slight trend emerged when considering quadrants. Cores extracted from quadrants Q3 and Q4, particularly in the middle section (L31-L32), displayed a slightly lower mean OPI (± 8.8) compared to quadrants Q1 and Q2 (±9.0). This subtle difference might warrant further investigation to determine if it can be attributed to potential exposure variations or minor inconsistencies in concrete mix properties across quadrants.

4.4 Impact of environmental emissions on the cooling tower

The petrochemical emissions discussed in the in chapter 2 have a variety of detrimental effects on the concrete cooling tower. The Sasol Secunda Natural Draft Cooling Towers are situated within a harsh petrochemical environment, characterized by a complex mixture of airborne emissions originating from various process plants. These emissions, including sulfur dioxide (SO2), nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and hydrogen sulfide (H2S), can significantly impact the durability and service life of the concrete structures within the facility. The continuous exposure to these pollutants, combined with the high humidity and temperature fluctuations inherent to cooling tower operations, creates a challenging environment for concrete, accelerating its deterioration and necessitating proactive mitigation strategies.

In cooling towers, sulfate attack manifests as a complex degradation mechanism driven by both physical and chemical processes. The primary source of sulfates is both the cooling water and the airborne SO_2. The airborne sulfur dioxide (SO_2) emissions from nearby industrial processes can also dissolve in the cooling water and settle on the tower surface, further increasing sulfate levels. The physical aspect of sulfate attack involves the crystallization of sulfate salts within the porous concrete matrix. As the water evaporates from the concrete surface, it leaves behind concentrated sulfate solutions that can crystallize and exert internal pressures. These pressures can exceed the tensile strength of the concrete, leading to cracking and spalling, particularly in regions with high evaporation rates, such as the upper sections of the cooling tower.

In the context of cooling towers, the combined physical and chemical effects of sulfate attack leads to structural damage, compromising the tower's integrity and performance. The presence of high temperatures, humidity fluctuations, and wetting-drying cycles further exacerbates the deterioration process. Therefore, understanding and mitigating sulfate attack is critical for ensuring the long-term durability and reliability of cooling towers in petrochemical environments. (Jeremy et al, 2013)

Hydrogen sulfide, often released in petrochemical processes, readily reacts with moisture and oxygen to form sulfuric acid. This acid, as discussed earlier, initiates sulfate attack on the concrete, leading to the dissolution of cement paste, the formation of expansive gypsum, and ultimately, structural degradation (Li et al 2019).

Particulate matter, consisting of fine solid particles and liquid droplets, can exert both physical and chemical damage on concrete. The physical impact involves the abrasion of the concrete surface due to the constant bombardment of particles, leading to erosion and exposing the inner layers to further degradation. Chemically, PM can be acidic or alkaline, depending on its composition. Acidic PM directly attacks the concrete, while alkaline PM can trigger alkali-aggregate reactions (AAR), a type of internal expansion that induces cracking and compromises structural integrity (Marinoni et al, 2003).

4.5 Water Chemistry Analysis results

The Basson index serves as a practical tool to measure the aggressiveness of water to concrete. This index calculation offers a useful approach to address the challenge of aggressiveness and aids in the selection of appropriate protective measures.

As per Basson and Addis in 1992 the following concentration limits were used to identify a water as corrosive to concrete:

- pH level < 7
- Chloride ion concentration > 1000 mg/L
- Sulphate ion concentration > 1000 mg/L
- Magnesium ion concentration > 100 mg/L
- Ammonia ion concentration > 100 mg/L

As shown in Table 4.6 the data obtained shows the pH level of the water being slghtly acidic, with levels of the ammonia and sulphate ion concentrations being on the higher end than the acceptable. With the limits mentioned above and the data below it can be seen that this water is potentially corrosive to concrete. Although the data showing a level of chloride ion concentration that is below the threshold limit for corrosiveness, the CTs undergo wetting and drying cycles. The chloride threshold level for corrosion initiation in reinforced concrete is not a fixed value. It is dependent on a multitude of factors, including cover thickness, ambient temperature, relative humidity, the electrochemical potential of the reinforcing steel, binder type, the ratio of bound to free chlorides, and the chloride-to-hydroxyl ion ratio (Nilsson et al., 1996). There is significant variation in reported chloride threshold levels, ranging from 0.02% to 3.08% of the binder's mass. Despite this large variability, a conservative value of 0.4% total chlorides by cement mass is commonly adopted by many researchers (Daigle et al., 2004).

The wetting and drying potentially could cause severe damage to the concrete and embedded reinforcing steel. The wetting and drying results in continuous movement of moisture through the concrete, and as a result increases durability problems in the CT. In the context of cooling towers, as water evaporates, the remaining water in the cooling tower basin becomes more concentrated in dissolved solids (salts and minerals) that were originally present in the makeup water. This concentration effect can occur expose the concrete to an accumulation of the aggressive ions tabulated below. While evaporation is the core principle of heat transfer in a natural draft cooling tower associated negative implications on concrete is possible. While these wetting and drying cycles are unavoidable in cooling tower operation, they can also have some negative consequences for the concrete structure which is evident from the visual inspection and durability test results presented in the preceding sections.

The data reveals significant variability in several key water chemistry parameters with potential consequences for the cooling tower structure.

The mean concentration for Chloride ions was measured at 378 mg/L, with some samples close to exceeding 1000 mg/L, the threshold for corrosive water suggested by Basson and Addis (1992). The high standard deviation (98.56 mg/L) indicates frequent fluctuations close to this limit, posing a possible risk of chloride-induced deterioration of the concrete structure and corrosion of embedded steel reinforcement. The average concentration of Sulphate ions (2355.9 mg/L) significantly surpasses the 1000 mg/L limit proposed by Basson and Addis (1992). While the specific influence of sulfates on corrosion depends on other factors, their presence alongside high chloride concentrations raises concerns about potential synergistic effects that could accelerate concrete degradation.

Table 4-6 Water Chemistry Data

Ionic Speciecs (No.entries 2201)	***Mean Value***	***Minium Value***	***Maximum Value***	***Standard Deviation***
Chloride (mg/L)	378	5.0	946.0	98.56
Calcium (mg/L)	13.5	1.2	815.5	20.73
Magnesium (mg/L)	14.0	3.4	46.8	3.43
Sulphate (mg/L)	2355.9	50.2	4741.5	564.80
pH	6.8	5.4	8.3	0.37
Conductivity (mg/L)	10125.0	1110.0	97220.0	2476.207
Ammonia (mg/L)	800.6	57.1	1622.9	248.33
Fluoride (mg/L)	427.5	27.2	3688.7	100.39
M Alkalinity (mg/L)	519.9	73.0	1225.0	152.89
Iron (mg/L)	14.8	0.2	59.0	6.78
Phosphate (mg/L)	15.1	0.2	88.1	12.33
Silica (mg/L)	148.8	22.5	341.10	36.94
Total suspended solids (mg/L)	2479.5	188.0	7916.0	988.51

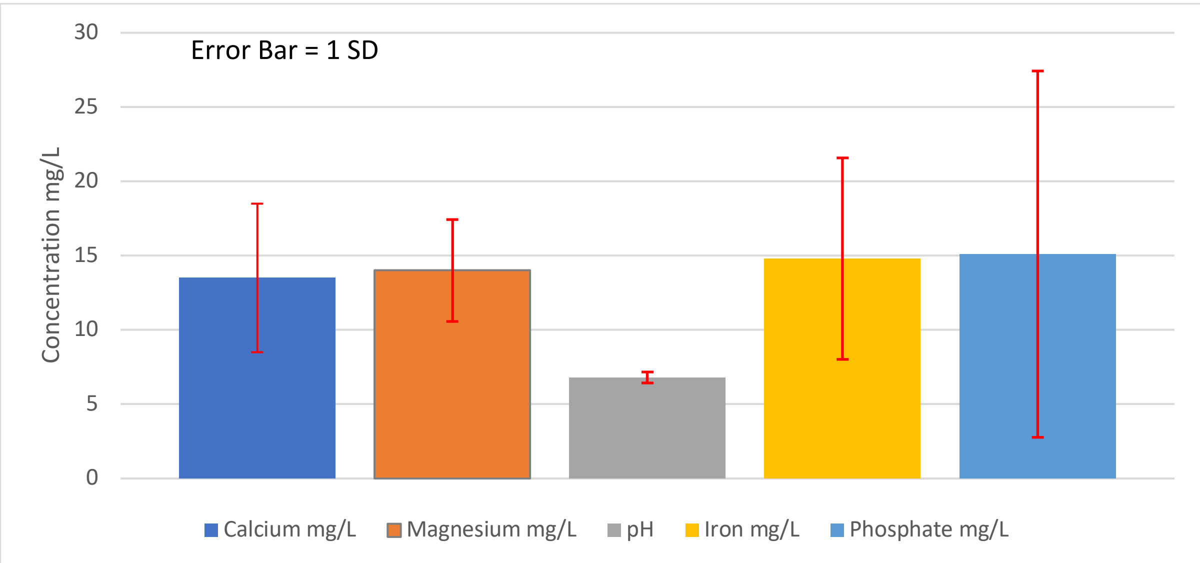

Figure 4-8 Water Chemistry Analysis of the cooling water(February 2017 – February 2023).

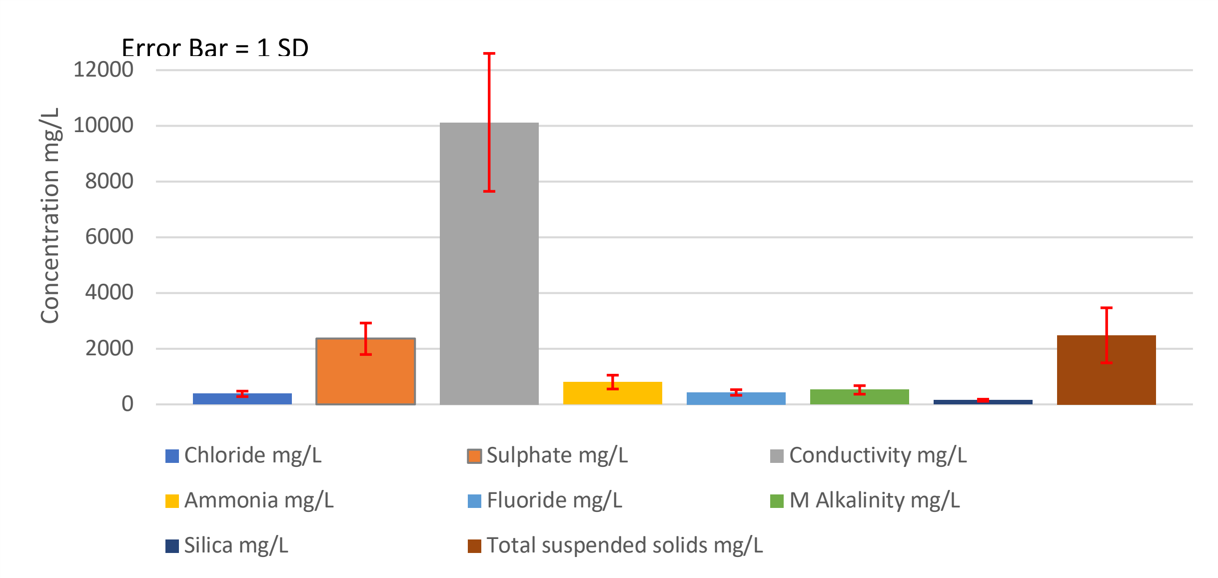

Figure 4-9 Water Chemistry Analysis of the cooling water(February 2017 – February 2023)..

The above water chemistry analysis shows the error bars relating to the variability in the concentration of each property being measured across multiple sample collections between 2017 and 2023. The larger error bars signify a higher degree of variation in the measured concentrations. This could be as a result of variations in the water source.

The significant variability observed in several key water chemistry parameters, particularly chlorides and sulfates, raises a concern about the potential for reinforcing steel corrosion in the cooling tower structure.

4.5.1 Basson Indices

The aggressiveness indices was calculated using the historical water data of the process CTs. For this study corrections were applied for turbulence, temperature and stagnancy. Due to the sometimes-turbulent conditions when there is an inflow of water and sometimes the stagnant case, when the water is still, all three corrections were applied. The leaching corrosion sub-index (LCSI) was calculated from the pH, and calcium ion concentration. A positive LCSI reveals the potential for water to dissolve the cement paste in concrete, a critical factor in its strength and durability. Values exceeding 1000 denote "very highly aggressive" leaching, posing a significant risk to concrete integrity (Basson & Addis 1992).

Calculated from magnesium, ammonium, and sulphate ion concentrations, the SCSI reflects the potential for aggressive salts in water to induce concrete deterioration through spalling. The spalling corrosion sub-index (SCSI) reveals a high value, driven by the process water's elevated ammonia ion concentrations. The high sulphate content further amplifies this effect, indicating an interaction between these aggressive ions (Beushausen et al. 2021). This suggests the presence of dissolved salts which is capable of initiating physical and chemical alterations within the cement paste (Basson & Addis 1992). This deterioration can manifest as delamination and spalling (surface flaking). The high SCSI value requires further investigation into the specific salt compositions and implementation of maintenance strategies to ensure the structural integrity and longevity of concrete exposed to this process water. The mean LCSI and SCSI scatter plot showing the variability over the 7 year period depicted in figures 4.10 and 4.11 with the overall aggressivity shown in figure 4.12.

The AI as can be seen from the calculations show the average value from 2017 to 2023 is in most instances significantly above the 1000 threshold. Daily LCSI and SCSI values were determined from the water chemistry data, and will be presented graphically in figures 4.10 and 4.11. Without considering turbulence, stagnancy and temperature the value is approximately 3500 and with the corrections applied the value is approximately 4000.

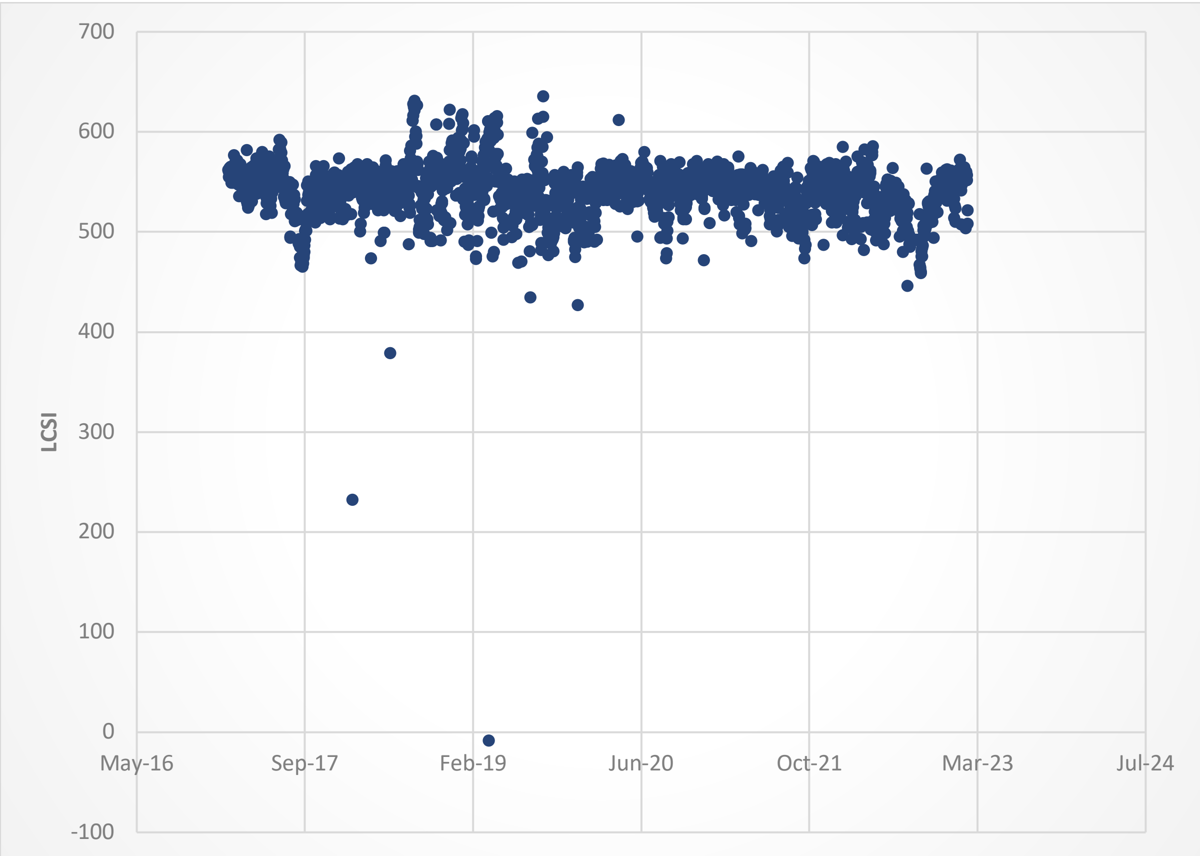

Figure 4-10 Scatter plot of the LCSI for Cooling Tower water.

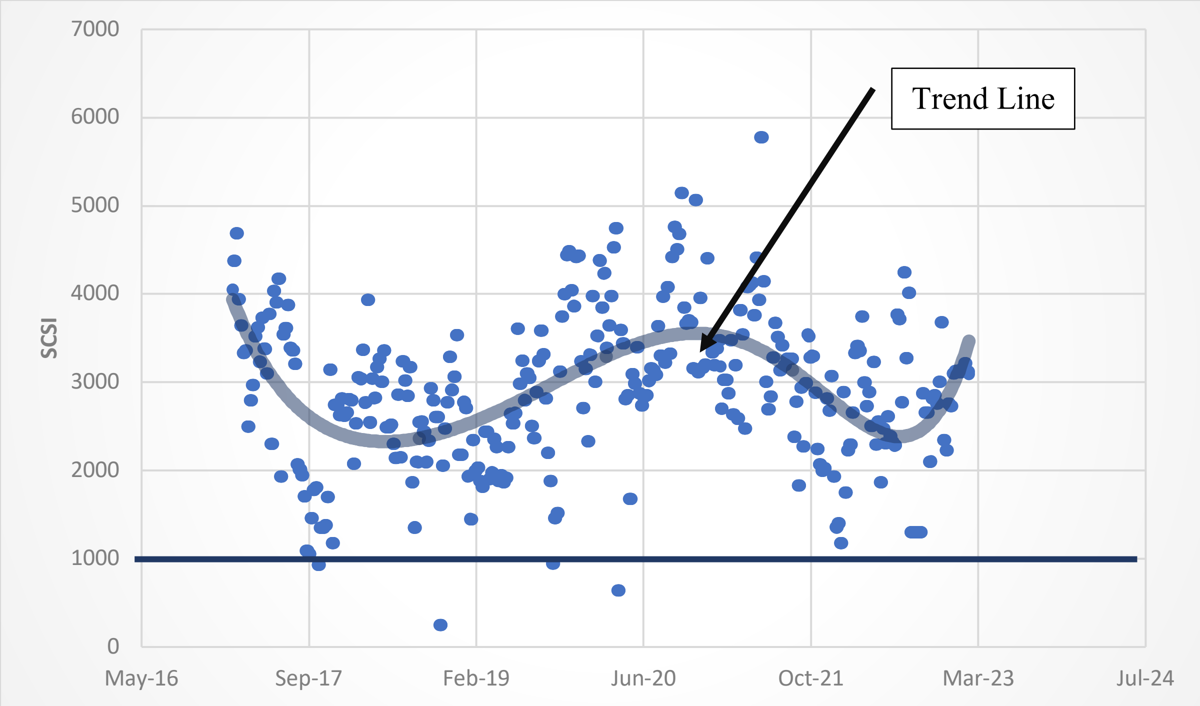

Figure 4-11 Scatter plot of the SCSI for Cooling Tower water.

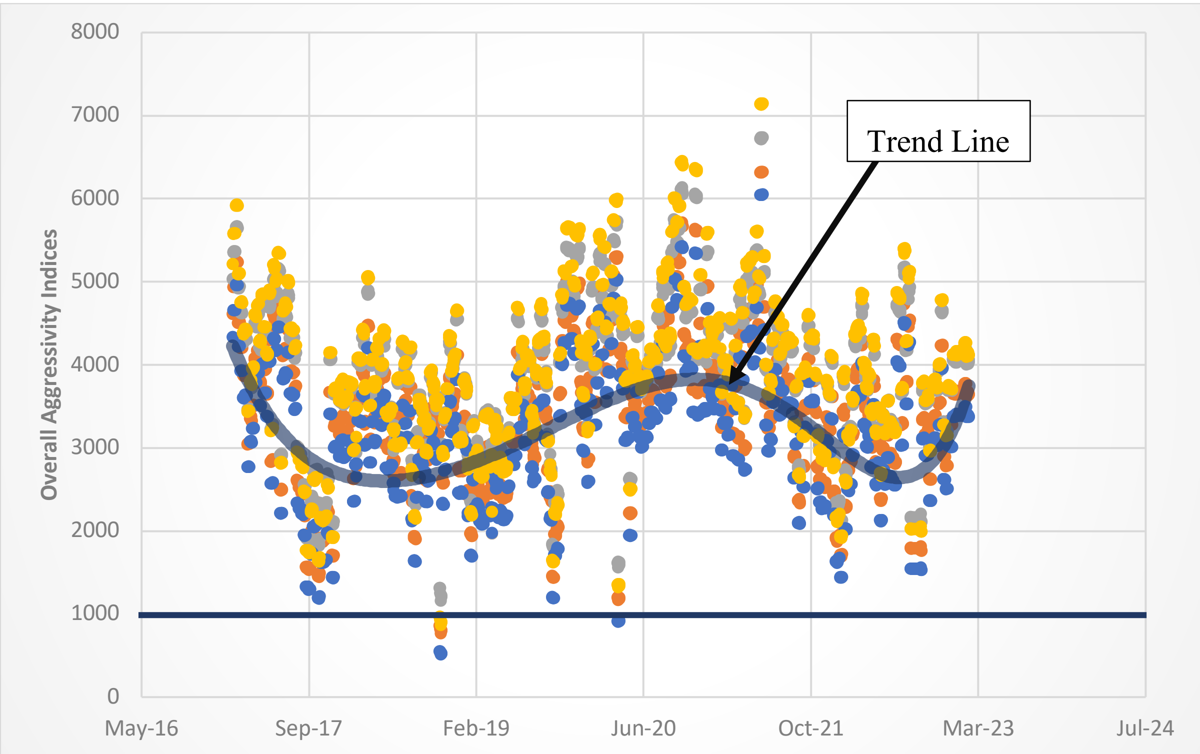

Figure 4-12 Overall Agressivity Index for Cooling Tower water

Figures 4.11 and 4.12 illustrate the temporal variation in the Spalling Corrosion Sub-Index (SCSI) and Overall Aggressivity Index (AI) of the cooling tower water over a seven-year period. The data reveals a distinct sinusoidal pattern in both indices, suggesting a cyclical fluctuation in the water's aggressiveness towards the concrete. This cyclical behavior aligns with the concept of seasonal variation, as the water chemistry is potentially influenced by changing environmental conditions throughout the year.

The observed peaks and troughs in the graphs could be attributed to seasonal factors. It is unclear whether colder or warmer temperatures influence the water chemistry however from the water chemistry data from the analysed 7 year period, the higher aggressiveness, as indicated by elevated SCSI and AI values coincides with colder months and follows a decline approaching September.

Furthermore, the seasonal variation in water chemistry could be linked to operational factors at the petrochemical plant. Certain processes or emissions might exhibit seasonal fluctuations, impacting the composition of the cooling water. Increased industrial activity during specific seasons will lead to higher concentrations of aggressive chemicals in the water, contributing to the observed peaks in the indices.

The implications of this seasonal variation are significant for the durability of the cooling tower. To further investigate this phenomenon, a more in-depth analysis is recommended. This could involve correlating the variations in the Basson indices with environmental data such as temperature, rainfall, and humidity. Additionally, examining operational data from the linked plants could reveal any seasonal patterns in processes or emissions that might influence water chemistry. By understanding the underlying causes of the seasonal variation, more effective strategies can be developed to mitigate its impact on the cooling tower's durability.

Based on the aggressiveness index values it can be deduced that the water in the CTs can be considered severely corrosive to the concrete of process water cooling towers. Corrosive and aggressive waters will accelerate the deterioration of concrete in cooling towers through leaching and spalling. These waters dissolve and remove soluble components from the concrete (leaching), weakening its structure. The frequent wetting and drying cycles associated with cooling tower operation has evidently caused chloride ions and other aggressive ions within the concrete to build up. As these ions penetrate the concrete matrix, they cause internal expansion and cracking, eventually leading to the observed flaking and detachment of concrete pieces (spalling). The defects that are a result of the aggressiveness of the water will lead to eventual loss of structural capacity and potential collapse.

4.6 Outlier detection and impact on analysis

Data points that deviate significantly from the expected distribution of a dataset are classified as outliers (Barnett et al., 1994). These outliers can have a substantial impact on statistical analyses.

The treatment of outliers depends on their origin. Outliers demonstrably caused by physical phenomena, such as sample contamination, instrument malfunction, or data entry errors, can be justifiably excluded from the analysis after verification. However, outliers with no apparent physical explanation require a more rigorous approach for confirmation using statistical criteria (Quinn and Keough, 2006).

This study implemented an approach to identify and eliminate outliers from the data. Outliers were defined as data points exhibiting statistically significant deviations from the theoretical distribution of the population, as determined by known population means and standard deviations. In this study, data points falling outside a predefined threshold based on the known population mean and standard deviation were excluded from the analysis.

The Grubb's test can be used as a statistical method to determine outliers when the mean and standard deviations of a data set are unknown. In the case of this study, the population averages and standard deviations were known.

4.7 Chapter Summary and Closure

The findings from the visual inspection of the cooling tower in a petrochemical environment were presented in this chapter. The investigation revealed significant concrete deterioration, primarily manifested as cracking, delamination, and spalling, concentrated in the upper sections of the tower. These defects align with the corrosion of embedded steel reinforcement, further exacerbated by severe environmental exposure. A critical observation was the uneven distribution of damage, with the upper levels showing a more pronounced deterioration compared to the lower sections. Further investigation is recommended to confirm the root cause of the uneven deterioration. This may involve analyzing wind patterns, water chemistry at various elevations, and moisture distribution throughout the structure. Understanding these factors is crucial for developing targeted repair strategies and ensuring long-term durability of cooling towers in harsh environments. Additionally, visual inspection revealed surface erosion and exposed aggregate, suggesting a combination of contributing factors. Significant variation in concrete quality even within close proximity of each other suggests potential inconsistencies in material properties, construction practices, or the presence of localized aggressive agents.

The cover meter data revealed a concerning trend of decreasing cover depth with increasing elevation across the cooling tower shell with variability in the results. This variation suggests potential inconsistencies during construction, where proper concrete placement and consolidation practices may not have been uniformly implemented across all lift levels (as shown in Table 4.2). Areas with significantly reduced cover depth, particularly those concentrated in the upper regions of the tower, are evidently more vulnerable to accelerated deterioration due to increased exposure to aggressive elements such as chlorides and sulfates. This observation aligns with the findings from the visual inspection, which identified spalling, discoloration, and softened cement paste, which are all indicative of concrete degradation and potential steel reinforcement corrosion.

The WSI results revealed a significant variation in the initial water absorption rate across the tower. Cores from the upper sections exhibited lower mean WSI values but larger porosity values, suggesting a denser microstructure at the surface concrete compared to the middle and bottom sections. This finding aligns with the visual inspection observations of more pronounced deterioration in the lower regions, potentially due to higher porosity and increased susceptibility to moisture ingress.

The CCI results highlighted a concerning trend of elevated chloride conductivity, particularly in the upper concrete layers. This indicates a higher potential for chloride ion penetration, likely due to factors like increased exposure to process water vapor and potentially higher chloride concentrations at these elevations. The observed variability in CCI values across quadrants within each elevation suggests potential inconsistencies in exposure conditions or concrete mix properties during construction.

The OPI results, on the other hand, indicated a relatively uniform resistance to oxygen diffusion throughout the tower height. However, a slight variation was observed between quadrants, with cores from Q3 and Q4 exhibiting a marginally lower mean OPI compared to Q1 and Q2. This subtle difference warrants further investigation to determine the underlying cause.

These findings emphasize the critical importance of considering durability characteristics during material selection and construction practices for structures exposed to harsh environments like petrochemical facilities. The observed trends in WSI and CCI underscore the need for targeted repair strategies to address the higher susceptibility to moisture and chloride ingress in the upper sections of the cooling tower

The calculated Basson indices, LCSI (leaching corrosion sub-index) and SCSI (spalling corrosion sub-index), further substantiated the aggressive nature of the process water used in the cooling processes. The high LCSI value indicated a risk of concrete leaching, while the elevated SCSI value suggested the potential for spalling due to aggressive salt interactions within the cement paste. The overall aggressiveness index (AI) consistently exceeded the critical 1000 threshold significantly, confirming the severely corrosive nature of the water.

These findings highlight the critical role of water chemistry in concrete durability. The observed trends suggest a high risk of corrosion and deterioration in the cooling tower structure.

The in-service durability performance of cooling towers within petrochemical facilities presents a unique challenge. Exposure to aggressive process water can lead to complex deterioration processes. Water sorptivity testing suggests potential for moisture ingress, while elevated chloride conductivity measurements raise concerns about chloride-induced corrosion of the embedded steel reinforcement. Furthermore, the presence of acidic water and the potential for synergistic effects from aggressive salt interactions within the concrete matrix can significantly compromise the long-term structural integrity of these critical cooling systems.

5. CONCLUSIONS AND RECOMMENDATIONS

The in-service durability of natural draft reinforced concrete cooling towers (CTs) operating in harsh petrochemical environments is a critical concern for the safety and longevity of these structures. This research aimed to gain valuable insights into this issue by investigating the Sasol Secunda Natural Draft Process Water Cooling Tower. The specific objectives were to:

- Assess the current condition of the cooling tower through visual inspections.
- Examine the influence of the harsh petrochemical environment on the tower's durability.
- Identify and analyze deterioration mechanisms relevant to cooling towers with contaminated water.
- Quantify the durability performance of the Sasol Secunda cooling towers using the Durability Index (DI) approach.

This chapter summarizes the key findings of the research presented in Chapter 4. It discusses how these findings address the research objectives and ultimately contribute to the overall aim of understanding the in-service durability of cooling towers in such environments. The chapter concludes by providing recommendations for future research and practical applications based on the study's outcomes.

5.1 Conclusions

Visual inspections of the Sasol Secunda Natural Draft Cooling Tower 245B revealed significant concrete deterioration, primarily manifested as cracking, spalling, and surface erosion. These defects were most prevalent in the upper levels of the tower, suggesting a correlation with the harsh environmental factors and the tower's design, which induces significant thermal gradients, with hotter conditions at the top. Fluctuations in temperature can cause thermal stresses within the concrete, leading to cracking and potential spalling as the material weakens. The evaporation process within the tower can result in higher moisture levels at the top. This moisture saturation can promote corrosion of the embedded steel reinforcement, leading to cracking and spalling due to expansive corrosion products (Dhawan et al 2019). The upper levels are also more likely exposed to higher concentrations of airborne contaminants or process water vapor. This can include higher exposure to higher wind speeds (SANS 10160-

3:2019). These aggressive elements can accelerate degradation of the concrete shell, promoting both cracking and spalling.

Additionally, visual inspection revealed surface erosion and exposed aggregate, suggesting a combination of contributing factors. Significant variation in concrete quality, even within close proximity, could be attributed to inconsistencies in material properties, construction practices, or the presence of localized aggressive agents within the process water in the cooling tower. The water chemistry is discussed later in this chapter.

5.2 Effect of harsh exposure environment on durability performance

The in-service durability of the Sasol Secunda cooling tower is influenced by the surrounding petrochemical environment. The various process plants release airborne emissions that can travel by wind and interact with the cooling tower structure. This study considered the impact of these emissions, including those from plants located farther away, on the concrete's durability. The presence of sulfur dioxide (SO_2) in the air, resulting from the combustion of fossil fuels, can lead to the formation of sulfuric acid (H_2SO_4)when combined with moisture. This acid attacks the concrete's cementitious matrix, causing it to weaken and deteriorate. Additionally, the presence of carbon dioxide (CO_2) can initiate carbonation, a process that reduces the concrete's alkalinity and compromises the protective layer around the steel reinforcement, making it susceptible to corrosion.

A comprehensive assessment for environmental classification is crucial (Chapter 3.3). This classification considers both the atmospheric emissions from surrounding plants and the aggressiveness of the cooling water itself. A thorough analysis of the cooling water chemistry was conducted to determine its potential to degrade concrete. By combining this water data with information on airborne emissions, the environment surrounding the cooling tower can be accurately classified as XD1, XD2 and XD3 according to relevant standards like BS EN 206-1:2000. Understanding the environmental classification is essential for selecting appropriate concrete materials and design considerations when planning future maintenance or repair strategies. Overall, this study has proven that the combined effects of these harsh environmental factors create complex deterioration process in cooling towers within petrochemical environments.

5.3 Effect Water Chemistry on the durability performance

Analysis of the cooling tower water chemistry revealed significant variability in key parameters with potential consequences for the concrete structure. The water exhibits a high leaching potential. This aggressive leaching, particularly targeting Ca(OH)2, induces significant softening of the concrete's cement paste. As a result, the cementing capacity of the surface deteriorates, resulting in compromised structural integrity and long-term performance of the cooling towers. The high sulfate content further amplifies this effect, indicating an interaction between these aggressive ions (Beushausen et al. 2021). This suggests the presence of dissolved salts capable of initiating physical and chemical alterations within the cement paste (Basson & Addis 1992). This deterioration can manifest as delamination and spalling (surface flaking). The high SCSI value requires further investigation into the specific salt compositions and implementation of maintenance strategies to ensure the structural integrity and longevity of concrete exposed to this process water. The mean LCSI and SCSI scatter plot showing the variability over the 7-year period is depicted in figures 4.10 and 4.11, with the overall aggressivity shown in figure 4.12.

Analysis of the cooling tower water chemistry revealed significant variability in key parameters with potential consequences for the concrete structure. The average chloride concentration (378 mg/L) approached the threshold for corrosive water (1000 mg/L) defined by Basson and Addis (1992), with some samples exceeding this limit. High standard deviation also indicated frequent fluctuations near this threshold, raising concerns about chloride-induced deterioration and steel corrosion. Additionally, the average sulfate concentration (2355.9 mg/L) significantly surpassed the 1000 mg/L limit, suggesting potential for combined effects with chlorides to accelerate concrete degradation. The wetting and drying cycles experienced by the cooling tower further exacerbate these issues. As water evaporates, the remaining water in the cooling tower basin becomes more concentrated in dissolved solids (salts and minerals) that were originally present in the makeup water. This concentration effect can lead to the accumulation of harmful substances within the concrete, accelerating deterioration processes.

The calculated Basson indices, LCSI (leaching corrosion sub-index) and SCSI (spalling corrosion sub-index), further substantiated the aggressive nature of the process water used in the cooling processes. The high LCSI value indicated a potential for dissolving the concrete's cement paste, compromising its strength and durability. The elevated SCSI value suggested the potential for spalling due to aggressive salt interactions within the cement paste. The overall Aggressiveness Index (AI) consistently exceeded the 1000 threshold, ranging from a minimum of 871 to a maximum of 7147, confirming the water's severe corrosivity.

The combined effects of chloride accumulation from wetting and drying cycles, high sulfate concentrations, and the overall aggressiveness of the water contribute to the observed deterioration of the cooling tower structure. These aggressive elements accelerate leaching, weakening the concrete structure, and promote spalling due to internal expansion and cracking. Left unaddressed, these defects will lead to a gradual loss of structural capacity and potentially compromise the tower's integrity.

5.4 Discussion on the Durability Index Testing Approach

The Water Sorptivity Index (WSI) results indicated a variation in the concrete's initial water absorption rate across the tower height (Chapter 4.1.1.1). Lower WSI values generally correspond to lower porosity and hence greater resistance to moisture ingress. The upper sections exhibited a denser microstructure with a slower initial water absorption rate compared to the middle and bottom sections. However, porosity values in the upper sections were higher than the middle and bottom sections. This seemingly contradictory observation suggests that factors beyond just total porosity, such as pore size distribution and connectivity, influence water absorption.

The Chloride Conductivity Index (CCI) measurements reveal a concerning trend of increased susceptibility to chloride ingress and potential corrosion in the upper sections of the Secunda Cooling Tower. Table 4.5 shows significantly higher CCI values in the top compared to the middle and bottom sections of the tower. This indicates a greater ease of chloride ion movement through the concrete in these areas, raising concerns about potential corrosion of embedded steel reinforcement. The data also exhibits considerable variation in CCI values across different core locations and within the same tower height. This variability suggests potential inconsistencies in the concrete properties, potentially affecting its durability throughout the structure. The high variability between the results could be as a results of various factors, including poor construction practices and variations in the concrete mix design. The use of sliding formwork during construction is suspected to have impacted the quality of concrete poured at higher elevations, since control is reduced.

The Oxygen Permeability Index (OPI) values exhibited relatively small variations between the tower's top, middle, and bottom sections (Chapter 4.1.1.3). This indicates that the concrete's resistance to oxygen ingress remains fairly consistent throughout the tower's height. While the overall variation across elevations was minimal, a slight trend emerged when considering quadrants. Cores from quadrants Q3 and Q4 displayed a slightly lower mean OPI compared to Q1 and Q2.

The results from the durability index testing highlight the complex interplay between various factors affecting the concrete's in-service durability performance. While WSI indicated a denser microstructure in the upper sections, higher CCI values in these areas suggest increased susceptibility to chloride ingress. This is further supported by the observed trend of increased spalling and delamination at the upper levels. The combined effects of exposure conditions, material properties, and potentially poor quality control/assurance and construction practices have likely contributed to the observed deterioration in the cooling tower structure.

5.5 Recommendations for further research

Based on the findings of this study, the following recommendations are made for further research:

1. **Interior Shell Assessment:** Extend the durability assessment to include the interior of the cooling tower shell. This would provide a more comprehensive understanding of the deterioration mechanisms and their impact on the overall structural integrity.
2. **Contamination Testing:** Conduct contamination testing, including chloride content, carbonation depth, and sulfate contamination assessments. This additional data would enhance the accuracy of service life prediction (SLP) models and inform targeted repair strategies.
3. **Petrographic Analysis:** Perform a detailed petrographic analysis of concrete cores to gain deeper insights into the microstructural changes and deterioration mechanisms at play. This analysis could help identify specific mineral phases and their contribution to the observed deterioration.
4. **Corrosion Rate Measurement:** Implement corrosion rate measurements to quantify the rate of steel reinforcement corrosion in different sections of the cooling tower. This data would be invaluable for predicting the remaining service life and planning appropriate maintenance interventions.

5. **Long-Term Monitoring:** Establish a long-term monitoring program to track the progression of deterioration and assess the effectiveness of any implemented repair or mitigation strategies. This would provide valuable data for future research and inform best practices for the maintenance and preservation of cooling towers in harsh environment

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APPENDIX A1 – CORE LOG

Table 0-1 Core log with summary of visual assessment findings

Core ID	***Quadrant***	***Lift Number***	***Guy Rope***	***Core Diameter (mm)***	***Length (mm)***	***Visual Observations***
212	1	12	31	102	150	Light grey, moist, some cracking around aggregate
211	1	13	30	102	152	Light grey, dry, hairline cracks
210	1	14	31	102	103	Dark grey, dry, some cracking around aggregate
209	1	15	30	102	133	Light grey, dry, hairline cracks, some voids visible
208	1	34	31	102	127	Light grey, dry, some cracking around aggregate, visible voids
207	1	35	30	102	101	Light grey, dry, hairline cracks, visible voids
206	1	36	31	102	54	Light grey, dry, hairline cracks visible
205	1	37	30	102	61	Light grey, dry, hairline cracks, voids visible
204	1	75	31	102	82	Light grey, dry, some cracking around aggregate, voids visible
203	1	76	30	102	81	Light grey, dry, hairline cracks,

202	1	77	31	102	95	Light grey, dry, some cracking around aggregate
201	1	78	30	102	96	Light grey, dry, hairline cracks
224	2	13	20	102	85	Light grey, moist, some cracking around aggregate
223	2	14	21	102	83	Dark grey, dry, hairline cracks, voids visible
222	2	15	20	102	62	Dark grey, dry, some cracking around aggregate
221	2	16	21	102	87	Light grey, dry, hairline cracks, some voids
220	2	36	20	102	60	Light grey, dry, some cracking around aggregate, voids visible
219	2	37	21	102	72	Light grey, dry, hairline cracks
218	2	38	20	102	96	Light grey, dry, hairline cracking visible, voids visible
217	2	39	21	102	100	Light grey, dry, hairline cracks
216	2	99	20	102	105	Light grey, dry, some cracking around aggregate, few voids visible
215	2	100	21	102	105	Light grey, dry, hairline cracks
214	2	101	20	102	102	Light grey, dry, some cracking around aggregate
213	2	102	21	102	84	Light grey, dry, hairline cracks, few voids

236	3	13	54	102	120	Light grey, moist, some cracking visible, few voids visible
235	3	14	55	102	115	Dark grey, dry, hairline cracks, few voids visible
234	3	15	54	102	122	Dark grey, dry, some cracking around aggregate, few voids visible
233	3	16	55	102	112	Light grey, dry, hairline cracks visible
232	3	30	54	102	120	Light grey, dry, some cracking around aggregate visible
231	3	31	55	102	122	Light grey, dry, hairline cracks
230	3	32	54	102	104	Light grey, dry, hairline cracks
229	3	33	55	102	97	Light grey, dry, hairline cracks, few voids
228	3	68	54	102	122	Light grey, dry, some cracking around aggregate visible
227	3	69	55	102	118	Light grey, dry, hairline cracks, few voids
226	3	70	54	102	102	Light grey, dry, few voids visible
225	3	71	55	102	95	Light grey, dry, hairline cracks, few voids visible
248	4	13	13	102	125	Light grey, moist, few voids

247	4	14	12	102	120	Light grey, dry, hairline cracks, few voids
246	4	15	13	102	110	Dark grey, dry,
245	4	16	12	102	78	Light grey, dry, hairline cracks, some voids visible
244	4	30	13	102	118	Light grey, dry, few voids visible
243	4	31	12	102	92	Light grey, dry, hairline cracks, few voids
242	4	32	13	102	82	Light grey, dry, some cracking around aggregate, few voids
241	4	33	12	102	126	Light grey, dry, hairline cracks, few voids
240	4	68	13	102	114	Light grey, dry, some cracking around aggregate, few voids
239	4	69	12	102	103	Light grey, dry, hairline cracks, few voids
238	4	70	13	102	114	Light grey, dry, some cracking around aggregate, few voids
237	4	71	12	102	132	Light grey, dry, hairline cracks, few voids

APPENDIX A2 – GENERAL PHOTOGRAPHS

Figure 0-1 - Overall image of CT 245B and the core drilling rig being aligned into place

Figure 0-2 Marking out of core location and after core was extracted

Figure 0-3 General photographs of the extraction process

Figure 0-4 Core extracted from Quarter 1 level 14

Figure 0-5 Cores extracted from Quarter 2 level 15

Figure 0-6 Core extracted from Quarter 3 level 70

Figure 0-7 Core extracted from Quarter 4 level 68

APPENDIX A3 - OPI RAW DATA

Bottom – Q1 and Q2

Scan	Time	102 (VDC)	103 (VDC)	104 (VDC)	106 (VDC)	107 (VDC)	108 (VDC)	109 (VDC)	110 (VDC)
1	2023/02/24 12:42:56:484	0.094491418	0.106987	0.108249	0.10643016	0.10576198	0.10529737	0.10717077	0.10690805
2	2023/02/24 12:57:56:380	0.045641566	0.082094	0.079663	0.066082935	0.090428404	0.096834077	0.084000968	0.070015086
3	2023/02/24 13:12:56:334	0.02435298	0.064088	0.06018	0.043247172	0.077824325	0.089149453	0.066776545	0.046603992
4	2023/02/24 13:27:56:369	0.013735487	0.050568	0.046175	0.029142842	0.067346045	0.08228836	0.053685687	0.031322404
5	2023/02/24 13:42:56:380	0.008117541	0.040303	0.035934	0.020086547	0.058553837	0.07612149	0.04353923	0.021316803
6	2023/02/24 13:57:56:369	0.00502014	0.032356	0.028232	0.014035985	0.051155086	0.070675826	0.035652747	0.014707452
7	2023/02/24 14:12:56:340	0.003283458	0.026156	0.022388	0.009934455	0.044720998	0.065477573	0.02924549	0.010245591

8	2023/02/24 14:27:56:337	0.002314583	0.021274	0.017889	0.007094787	0.039261663	0.060872088	0.024180679	0.007237341
9	2023/02/24 14:42:56:341	0.001750992	0.017391	0.014387	0.005125658	0.034544405	0.05661792	0.02003913	0.005142095
10	2023/02/24 14:57:56:378	0.00140383	0.014261	0.011638	0.003757303	0.030503455	0.052777277	0.016707664	0.003700311
11	2023/02/24 15:12:56:356	0.001226845	0.011769	0.009482	0.002784184	0.026970551	0.049228021	0.013964623	0.00269318
12	2023/02/24 15:27:56:346	0.001125089	0.009731	0.00774	0.002067798	0.023873602	0.045959467	0.011736932	0.002014751
13	2023/02/24 15:42:56:373	0.001037294	0.008061	0.006358	0.00156793	0.021181004	0.042942178	0.009871846	0.001513569
14	2023/02/24 15:57:56:374	0.000990169	0.006701	0.00525	0.001195775	0.018793164	0.040109221	0.008292295	0.001136409
15	2023/02/24 16:12:56:344	0.000956831	0.005592	0.004375	0.00095096	0.016725631	0.037535768	0.007014942	0.000893784
16	2023/02/24 16:27:56:342	0.000935538	0.004666	0.003648	0.000747289	0.014883586	0.035131747	0.005939456	0.000708654

17	2023/02/24 16:42:56:359	0.000904993	0.003895	0.003051	0.0006058	0.013278656	0.032909437	0.005058033	0.000582167
18	2023/02/24 16:57:56:356	0.000904469	0.003277	0.002582	0.000503033	0.011842158	0.030825195	0.004314083	0.000499212
19	2023/02/24 17:12:56:364	0.000883874	0.002763	0.002219	0.000441784	0.010588108	0.028911971	0.003667856	0.000407222
20	2023/02/24 17:27:56:358	0.000888936	0.002348	0.001912	0.000374762	0.009455345	0.027121397	0.003141568	0.000368618
21	2023/02/24 17:42:56:377	0.000872529	0.00198	0.001659	0.000345534	0.008494779	0.025495008	0.002720992	0.000328536
22	2023/02/24 17:57:56:380	0.000867467	0.001694	0.001465	0.000323192	0.007615524	0.023939229	0.002346065	0.000300611
23	2023/02/24 18:12:56:374	0.000875844	0.001468	0.0013	0.000289869	0.006801699	0.022416395	0.002018179	0.000280242
24	2023/02/24 18:27:56:360	0.000867467	0.001249	0.001142	0.000253565	0.006110355	0.02107631	0.001776213	0.000279749

Bottom Q3 and Q4

Scan	Time	102 (VDC)	103 (VDC)	104 (VDC)	106 (VDC)	107 (VDC)	108 (VDC)	109 (VDC)	110 (VDC)
1	2023/02/20 13:25:17:487	0.096747	0.106842	0.10713	0.116677	0.109056	0.107428	0.100821	0.108476
2	2023/02/20 13:40:17:337	0.031089	0.075887	0.08724	0.109901	0.087312	0.105952	0.028479	0.062961
3	2023/02/20 13:55:17:337	0.012063	0.055549	0.07113	0.102246	0.070205	0.103005	0.009609	0.038372
4	2023/02/20 14:10:17:337	0.005299	0.041527	0.058676	0.095291	0.057174	0.100125	0.003667	0.024164
5	2023/02/20 14:25:17:337	0.002706	0.031493	0.048815	0.08895	0.047038	0.097426	0.001702	0.015611
6	2023/02/20 14:40:17:337	0.001676	0.024152	0.040912	0.083196	0.039023	0.094826	0.000995	0.010229
7	2023/02/20 14:55:17:337	0.001248	0.018703	0.034464	0.077844	0.03252	0.092261	0.000734	0.006812

8	2023/02/20 15:10:17:337	0.001078	0.014581	0.029177	0.072938	0.027266	0.089817	0.000645	0.004597
9	2023/02/20 15:25:17:337	0.001009	0.011426	0.024798	0.068425	0.02299	0.087461	0.000616	0.003128
10	2023/02/20 15:40:17:337	0.000964	0.008999	0.021126	0.064189	0.019423	0.085155	0.00061	0.002189
11	2023/02/20 15:55:17:337	0.000945	0.007129	0.018093	0.060327	0.016496	0.082931	0.000584	0.001532
12	2023/02/20 16:10:17:337	0.000934	0.005685	0.015513	0.056674	0.014009	0.080753	0.000586	0.001129
13	2023/02/20 16:25:17:337	0.000923	0.004535	0.013356	0.053336	0.011974	0.078671	0.00057	0.000817
14	2023/02/20 16:40:17:337	0.000925	0.003644	0.011509	0.050192	0.010247	0.076645	0.000586	0.00065
15	2023/02/20 16:55:17:337	0.000927	0.002955	0.009959	0.047284	0.008801	0.07469	0.000586	0.000519
16	2023/02/20 17:10:17:337	0.000917	0.002425	0.00864	0.044542	0.007545	0.072763	0.00057	0.000441

17	2023/02/20 17:25:17:337	0.000919	0.002005	0.007535	0.042028	0.00652	0.070918	0.000557	0.00037
18	2023/02/20 17:40:17:337	0.000908	0.001655	0.006558	0.039635	0.005624	0.069126	0.000551	0.000329
19	2023/02/20 17:55:17:337	0.000901	0.001353	0.0057	0.0374	0.004888	0.067405	0.000561	0.00029
20	2023/02/20 18:10:17:337	-2.62E-06	6.12E-06	-8.82E-07	1.06E-05	-9.40E-06	1.26E-05	-2.78E-06	-3.94E-06
21	2023/02/20 18:25:17:337	0.000896	0.000976	0.004375	0.033321	0.003666	0.064029	0.000547	0.000256
22	2023/02/20 18:40:17:337	0.000893	0.000834	0.003862	0.031502	0.003213	0.062427	0.000533	0.000223
23	2023/02/20 18:55:17:337	0.000883	0.000715	0.003401	0.029761	0.002808	0.060864	0.000525	0.000208
24	2023/02/20 19:10:17:337	0.00089	0.000643	0.003017	0.028135	0.002465	0.059353	0.000531	0.000213

Middle

Scan	Time	102 (VDC)	103 (VDC)	104 (VDC)	106 (VDC)	107 (VDC)	108 (VDC)	109 (VDC)	110 (VDC)
1	2023/02/23 09:15:47:410	0.097683251	0.102929	0.107417	0.112238	0.093653	0.10396	0.104208	0.088953
2	2023/02/23 09:30:47:259	0.004656746	0.04291	0.094593	0.104324	0.043401	0.089877	0.072243	0.039866
3	2023/02/23 09:45:47:259	0.000922796	0.02019	0.083655	0.097041	0.021927	0.078191	0.051655	0.019257
4	2023/02/23 10:00:47:259	0.000888062	0.010077	0.074396	0.090548	0.011694	0.068526	0.037836	0.009727
5	2023/02/23 10:15:47:259	0.000881953	0.005272	0.066276	0.084436	0.006462	0.060166	0.028084	0.005078
6	2023/02/23 10:30:47:259	0.000884921	0.002877	0.059207	0.078831	0.003728	0.053074	0.021157	0.002783
7	2023/02/23 10:45:47:259	0.000885445	0.001681	0.053079	0.073742	0.002288	0.04696	0.016084	0.001589
8	2023/02/23 11:00:47:259	0.000884396	0.001083	0.047783	0.069156	0.001499	0.041729	0.012364	0.000991
9	2023/02/23 11:15:47:259	0.000881081	0.000749	0.043002	0.064779	0.001068	0.037123	0.009582	0.000687
10	2023/02/23 11:30:47:259	0.000884223	0.000599	0.038864	0.060845	0.000841	0.033111	0.007459	0.000511
11	2023/02/23 11:45:47:259	0.000884572	0.000517	0.035184	0.057206	0.000708	0.029609	0.005872	0.000436
12	2023/02/23 12:00:47:259	0.000890332	0.000466	0.031919	0.053854	0.000671	0.026561	0.004679	0.00039
13	2023/02/23 12:15:47:259	0.000890156	0.000444	0.028971	0.050679	0.000636	0.023826	0.003758	0.000377

14	2023/02/23 12:30:47:259	0.000883874	0.00043	0.026335	0.047716	0.000601	0.021374	0.003017	0.000342
15	2023/02/23 12:45:47:259	0.000888587	0.000419	0.02396	0.044954	0.000582	0.019224	0.002486	0.00036
16	2023/02/23 13:00:47:259	0.000884921	0.000429	0.021844	0.042383	0.000562	0.017291	0.002048	0.000353
17	2023/02/23 13:15:47:259	0.000885619	0.000412	0.019967	0.040068	0.000582	0.015621	0.001728	0.000338
18	2023/02/23 13:30:47:259	0.000884396	0.000405	0.018237	0.037823	0.000561	0.01409	0.001475	0.000345
19	2023/02/23 13:45:47:259	0.000891728	0.000404	0.016712	0.035792	0.00058	0.012751	0.001285	0.000345
20	2023/02/23 14:00:47:259	0.000892077	0.000423	0.015321	0.033836	0.000556	0.011508	0.001113	0.000335
21	2023/02/23 14:15:47:259	0.000892426	0.000424	0.014056	0.032019	0.000562	0.010413	0.000996	0.000337
22	2023/02/23 14:30:47:259	0.000901676	0.00044	0.012929	0.030332	0.000576	0.009454	0.000921	0.000347
23	2023/02/23 14:45:47:259	0.000893997	0.000414	0.011866	0.028717	0.000563	0.008574	0.000853	0.000346
24	2023/02/23 15:00:47:259	0.000898011	0.000424	0.010944	0.02725	0.000568	0.007785	0.000791	0.000343

Top

Scan	Time	102 (VDC)	103 (VDC)	104 (VDC)	106 (VDC)	107 (VDC)	108 (VDC)	109 (VDC)	110 (VDC)
1	2023/02/22 11:54:02:454	0.099472	0.119799	0.000246	0.119671	0.116512	0.1254	0.11649	0.123535
2	2023/02/22 12:09:02:304	0.031948	0.093979	0.033941	0.024691	0.067443	0.038367	0.044325	0.073357
3	2023/02/22 12:24:02:304	0.012385	0.074861	0.056061	0.006626	0.041591	0.014284	0.019644	0.046094
4	2023/02/22 12:39:02:304	0.005411	0.060407	0.054896	0.002029	0.026636	0.005692	0.009383	0.030063
5	2023/02/22 12:54:02:304	0.002714	0.049212	0.049211	0.000762	0.017602	0.002366	0.004759	0.020092
6	2023/02/22 13:09:02:304	0.001648	0.040428	0.041102	0.000406	0.011841	0.000999	0.002552	0.013667
7	2023/02/22 13:24:02:304	0.001208	0.033418	0.036227	0.000294	0.008094	0.000425	0.001476	0.009422
8	2023/02/22 13:39:02:304	0.001039	0.027795	0.032369	0.00027	0.005641	0.0002	0.00097	0.006589
9	2023/02/22 13:54:02:304	0.000969	0.023227	0.027932	0.000253	0.003985	9.71E-05	0.000707	0.004658
10	2023/02/22 14:09:02:304	0.000946	0.019513	0.023881	0.000257	0.002882	4.89E-05	0.000576	0.003342
11	2023/02/22 14:24:02:304	0.000941	0.016447	0.020156	0.000233	0.002123	3.42E-05	0.000529	0.002457
12	2023/02/22 14:39:02:304	0.000941	0.013887	0.016428	0.00023	0.001615	1.26E-05	0.000483	0.001828
13	2023/02/22 14:54:02:304	0.000927	0.011726	0.012949	0.000215	0.001269	1.05E-05	0.000466	0.001387

14	2023/02/22 15:09:02:304	0.000922	0.009927	0.009579	0.000218	0.00105	2.09E-05	0.000466	0.001075
15	2023/02/22 15:24:02:304	0.000914	0.008451	0.006111	0.000219	0.000868	-5.78E-06	0.000438	0.00085
16	2023/02/22 15:39:02:304	0.000913	0.007199	0.002752	0.000203	0.000751	-7.01E-06	0.000443	0.000712
17	2023/02/22 15:54:02:304	0.000911	0.006159	-0.00069	0.000218	0.00068	-1.05E-05	0.000429	0.000593

APPENDIX A4 - WSI RAW DATA

Top

F – Front, M = Middle, B = Back (Of Core)

Core Location	M_{s0}(g)	3	5	7	9	12	16	20	25	M_{sV}(g)
Q3 L68F	221.26	223.52	224.12	224.48	224.8	225.14	225.61	225.93	226.29	240.46
Q3 L68M	271.47	273.22	273.64	273.881	274.06	274.33	274.63	274.83	275.07	288.4
Q3 L69M	252.3	254.75	255.4	255.78	256.06	256.49	256.91	257.23	257.6	268.35
Q4 L68F	252.8	255.22	255.73	256.088	256.44	256.93	257.36	257.77	258.15	270.66
Q4 L68M	239.41	242.17	242.91	243.08	243.45	213.99	244.38	244.69	244.93	256.69
Q4 L68B	252.78	254.84	255.21	255.44	255.61	256.02	256.44	256.72	256.99	271.68
Q4 L70B	232.66	235.74	236.21	236.62	236.9	237.31	237.79	238.19	238.58	248.21
Q4 L71M	232.31	235.33	235.77	236.25	236.5	236.97	237.43	237.92	238.27	251.5

Middle

Core Location	**M_{s0}(g)**	**3**	**5**	**7**	**9**	**12**	**16**	**20**	**25**	**M_{sv}(g)**
Q1 L34M	266.39	268.24	268.64	268.98	269.17	269.99	269.91	270.12	270.77	277.16
Q1 L34B	267.15	269020	269.58	269.8	269.94	270.31	270.59	270.85	271.07	275.93
Q2 L38M	251.97	252.79	253.09	253.28	253.48	253.69	253.91	254.33	254.33	262.23
Q2 L38M	257.82	258.89	259.19	259.91	259.47	259.64	259.86	260.16	260.16	267.47
Q3 L31M	261.08	262.62	262.9	263.18	263.43	236.7	263.89	264.35	264.35	270.23
Q3 L31B	262.23	263.48	263.7	263.88	264.1	264.31	264.59	264.83	264.83	272.22
Q4 L32F	254.38	256.49	256.64	256.84	256.95	257.08	257.19	257.39	257.39	264.73
Q4 L32B	276.81	278.25	278.52	278.23	278.96	279.21	279.52	279.9	279.9	285.68

Bottom

Core Location	M_{s0}(g)	3	5	7	9	12	16	20	25	M_{sv}(g)
Q1 L12F	270.94	271.66	271.87	272.29	272.18	272.37	272.59	272.62	272.89	280.12
Q1 L12B	281.6	283.13	283.36	283.64	284.06	284.22	284.48	284.58	284.93	291.1
Q1 L15M	281.24	282.47	282.71	283.04	283.4	283.48	283.71	283.89	284.17	291.54
Q1 L15B	276.96	278.62	278.96	279.14	279.52	279.56	279.75	279.92	280.17	287.94
Q2 L16B	271.7	373.78	274.18	274.74	275.27	275.57	275.78	276.1	276.58	282.92
Q3 L13M	281.42	283.88	284.38	284.9	285.21	285.84	286.32	286.62	287.18	292.15
Q3 L13B	253.46	255.14	255.56	255.98	156.12	256.44	256.7	256.87	257.29	264.69
Q3 L16F	254.54	255.52	255.74	256.13	256.45	256.45	256.59	256.93	257.05	265.3
Q3 L16B	277.35	279.73	280.21	280.71	280.87	281.16	281.48	281.73	282.2	287.85
Q4 L14F	275.04	276.77	277.12	277.61	277.83	277.97	278.2	278.55	278.82	285.32
Q4 L14B	297.6	282.34	282.92	283.47	283.79	283.89	284.63	284.64	284.86	29160
Q4 L15F	276.9	277.53	277.62	277.76	277.87	277.89	278.09	278.15	278.21	287.59
Q4 L15B	278.93	280.37	280.74	281.08	281.18	281.42	281.67	281.86	282	288.58

APPENDIX A5 – CCI RAW DATA

Top

Core Location	*V*	*mA*
Q2 L100F	8.37	178
Q3 L69F	7.57	183
Q1 L75F	9.7	320
Q2 L102F	9.91	312
Q3 L 69F	5.56	194
Q4 L70F	8.11	165
Q4 L71F	5.9	116
Q1 L77F	8.3	261

Middle

Core Location	*V*	*mA*
Q3 L30B	6.52	22
Q4 L33F	5.09	46
Q1 L34F	8.75	32
Q2 L39B	7.57	45
Q1 L35M	5.37	49
Q2 L39F	6.69	51
Q3 L30F	4.61	27
Q4 L33B	6.07	16

Bottom

Core Location	*V*	*mA*
Q1 L13F	6.13	34
Q1 L13M	6.79	19
Q1 L15F	4.08	52
Q2 13B	6.87	38
Q2 16M	7.45	37
Q3 14F	5.99	37
Q3 16M	5.39	32
Q4 14M	6.75	22
Q4 16B	4.75	34

APPENDIX A6 – BASSON INDEX CALCULATION

Property	Test Method	Units	Value	Formula	Index
pH	SANS 5011:2005	1 ÷ (Log H)	V_1 =	N_1 = 200 x (9.5-6.8) = 540 N_1 = 200 x (9.5-6.8) = 540	N_1
Calcium hardness (as $CaCO_3$)	SANS 6265:2006	mg/L	V_3 = N_3 = 2.2 × (500 – V_3)	N_3 = 2.2 x (500-13.5) = 1070.3	N_3
Total ammonium ion (as NH_4)	SANS 5217:2010 SANS 5218:2007	mg/L	V_4	N_4 = 10 x 800.6 = 8006.0	N_4
Magnesium ion (as Mg)	SANS 6265:2006	mg/L	V_5	N_5 = 0.6 x 14 = 8.4	N_5
Total sulphate ion (as SO_4)	SANS 6310:2005 SANS 6056:2007	mg/L	V_6	N_6 = 0.3 x 2355.9 = 706.77	N_6
Chloride ion content (as Cl)	SANS 374:2005	mg/L	V_7	N_7 = 0.2 x 378 = 75.6	N_7
Indices of standard conditions					
Leaching corrosion sub-index	LCSI	***LCSI*** = (N_1 + N_2 + N_3) ÷ 3			

		= (540+1070) ÷ 3 = **536.67**
Spalling corrosion sub-index	SCSI	***SCSI*** = (N_4 + N_5 + N_6) ÷ 3 = (8006.0 + 8.4 + 706.77) ÷ 3 = **2907.06**
Aggressiveness index	N	N = LCSI + SCSI = 536.67 + 2907.06 = **3443.73**
To correct for:	**Formula**	
Turbulence	Turbulance = (LCSI x 1.75) + SCSI = (536.67 x 1.75) + 2907.06 = **3846.23**	
Stagnancy	Stagnancy = (LCSI x 0.5) + SCSI = (536.67 x 0.5) + 2907.06 = **3175.40**	
Temperature	Temperature factor = 1 + [0.05 × (T – 20)] where T = 22.57 = **1.13** $LCSI_c$ = 536.67 x 1.13 = **605.63** $SCSI_c$ = 2907.06 x 1.13 = **3284.98** N_c = 605.63 + 3284.98 = **3890.61**	