DISSERTATION FOR THE DEGREE OF MASTERS IN INFRASTRUCTURE
MANAGEMENT AND MAINTENANCE

Dissertation

Fibre cement boards as permanent formwork for reinforced concrete elements

Prepared by:

Naashif Mowzer

Supervised by:

Hans Beushausen

Co-Supervised by:

Nicholas Jarratt

Dissertation/Thesis submitted in fulfilment of the requirements for the degree of

“Masters in Infrastructure Management and Maintenance”

Department of Civil Engineering

University of Cape Town, Private Bag Rondebosch, 7700

South Africa 7700

Declaration

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own. This thesis/dissertation has been submitted to the Turnitin module (or equivalent similarity and originality checking software) and I confirm that my supervisor has seen my report and any concerns revealed by such have been resolved with my supervisor.

Signed by candidate

Signature:… ………………… Date: 07 February 2023

Acknowledgements

I would like to express my gratitude to the Almighty for all the opportunities that have come my way. I testify to your Oneness and reaffirm my belief that you are the Most High.

I want to express my thanks to my wife for all her love and support throughout the challenges we had to face. I cannot begin to convey how grateful I am to have you by my side, and I hope it will always be.

I am grateful to my two children, who have developed alongside me as I pursued my education, for never ceasing to amaze me.

I wish to express my gratitude to my mother for raising me and being by my side throughout my life.

To my sister, who remained at my back pushing me to be better, I hope that you find success in all areas of your life.

I want to express my gratitude to my extended family for bearing with me and easing my responsibilities. I am hoping I can provide the same for you.

I want to express my gratitude to the University of Cape Town personnel for helping me to extend my horizons through the knowledge I have acquired. A special thanks my supervisor and co-supervisor, Professor Hans Beushausen and Nicholas Jarratt, for guiding me through my research

The journey has been long and difficult, yet these difficulties have helped you grow. As there is still lots left for you to experience and overcome, may you always be eager to take the initiative.

Abstract

Formwork operations constitute the most expensive and time-consuming activity in the construction of concrete structures. A significant factor in the construction's time and cost components is the use of temporary formwork systems which have reusability limitations. Permanent formwork provides an alternative type of formwork that remains in place on the structure, and overcomes the reusability challenges of temporary formwork.

Due to its permanent adherence to the structure and material composition, permanent formwork may have benefits that exceed time and cost savings. By bonding to the structure for the duration of its service life, it may improve underlying concrete's durability.

The aim of this study was to assess if fibre cement boards, when used as a permanent formwork, can increase the durability of the underlying concrete and develop a sufficient bond to the concrete to act as a permanent formwork.

The testing procedure resulted in the production of composite and reference concrete samples, two concrete mixes were produced to simulate good-quality and poor-quality concrete. Durability index, bulk diffusion, and modified interface shear bond tests were conducted.

The modified shear bond test demonstrated that a bond with sufficient strength could be attained but further research is required to determine whether the bond is capable of withstanding differentials strains brought about by internal and external factors. Should proper controls not be in place, the bonding process may be susceptible to delamination. According to the durability index test results, the fibre cement boards did not improve nor decrease the concrete's durability. The results of the bulk diffusion tests showed that the composite samples had lower concentrations of chlorides indicating that the fibre cement boards provided protection to the underlying concrete. Additionally, the research showed that the fibre cement board functioned similarly good-quality concrete, indicating that under certain conditions, fibre cement concrete would be able to be specified as an equivalent concrete cover.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Background the study

Formwork operations constitute some of the most time and cost-intensive procedures in constructing reinforced concrete structures. These operations require that formwork be removed once the concrete reaches sufficient strength, which coupled with the industry norm of re-using formwork, leads to time restrictions. In addition, following formwork removal, proper concrete curing procedures must be followed. Curing refers to the process wherein cement hydration takes place and directly affects durability development. Protection can be provided using surface coating or by providing temporary physical coverage.

The construction industry currently has confidence in the use of temporary formwork systems. Temporary formwork refers to reusable formwork systems. These systems require considerable time and labour inputs to be used effectively. The time and labour inputs lead to significant cost impacts as Hanna (1998) explains that temporary formwork can amount to 40-60 percent of an overall structure's costs. Removing temporary formwork also requires the removal of shoring to access the temporary formwork boards. Shoring may be removed in sections to allow for the removal of temporary formwork and then be reinstated to support the concrete member in order to advance construction.

There is a type of formwork that remains in place after the concrete has been cast. This type of formwork is known as permanent formwork. Permanent formwork stays in place after the concrete has gained the required strength and becomes part of the final structure. This feature of permanent formwork makes it ideal for protecting the underlying concrete and has time and cost-saving benefits due to the elimination of the removal requirement of temporary formwork.

The world places a great deal of emphasis on concrete structures' durability as concrete infrastructure is crucial to modern society. Concrete structures must be able to maintain their serviceability to function as planned. From the perspective of durability, structures must be able to endure their environments in order to achieve their design life objectives. There are different types of concrete deterioration that have an impact on the overall durability of a structure. One particularly aggressive type is the entry of harmful chloride ions into the concrete, which can cause corrosion of the steel reinforcement.

Curing is a technique for increasing the durability of concrete. Curing enhances the concrete's resistance to harmful agents penetrating the cement matrix. Through the control of temperature and water loss from the concrete, the curing process promotes the development of a dense concrete matrix that is able to resist the penetration of harmful agents. There are various curing techniques, all of which concentrate on ensuring that there is sufficient water available for the cement matrix to develop effectively. Formwork has been left in place to allow the concrete to cure as it prevents the evaporation of water from the cement matrix. The utilization of permanent formwork serves as a barrier to protect against hazardous agents from reaching the underlying concrete. SANS 10100-2 code permits for the use of permanent formworks on structures by reducing the cover requirements for a structure. The code does not specify the type of permanent formwork materials to be used or their performance criteria and recommends that the engineer's discretion be applied when reducing cover.

Fibre cement is a material that combines a cement binder and a fibre-like component and has been utilized as permanent formwork. Steel, glass, synthetic fibres, and natural fibres are examples of fibre materials used in fibre cements. In comparison to concrete, they are reported to have greater tensile and flexural strengths, high dimensional stability, and to be resistant to harmful chemicals. Fibre cements have numerous uses in a variety of industries, including temporary and permanent formwork, fire prevention systems, building construction, and structural repairs.

In comparison to temporary formwork, the utilization of fibre cement board as permanent formwork may be beneficial for a structure. Concrete has been cured using formwork, and the same technique may be used with fibre cements boards as permanent formwork. A barrier to the entry of harmful agents, such as chlorides, into the underlying concrete may be created by placing the permanent formworks over the concrete. If this is the case, it may prolong the life of the structure by protecting it from deterioration. For fibre cement board to serve as a permanent formwork, it must be able to remain in place after casting. Therefore, understanding the bonding characteristics of fibre cement board and concrete is crucial.

1.2 Problem statement

Permanent formwork is considered advantageous for concrete since it can serve as a protective cover. However, there is not enough evidence to support this position. This investigation aims to fill the knowledge gap on the potential advantages of fibre cement board as a permanent formwork.

1.3 Aims and objectives

This research aims to investigate the durability influences, protective capabilities, and bond performance characteristics of fibre cement boards to the underlying concrete when used as a permanent formwork for reinforced concrete structures.

The following is a description of the research's objectives:

- Investigate whether fibre cement boards can serve as a curing method to enhance the durability of the underlying concrete structure
- Investigate whether fibre cement board acts as a protective cover to protect the underlying concrete from chloride ingress
- Investigate the bond characteristics between fibre cement boards and concrete to determine whether it can perform as a permanent formwork

1.4 Scope/limitations of the research project

The scope necessitates conducting experimental testing in a laboratory. Durability index, shear bond, and bulk diffusion testing were utilised to evaluate the performance of concrete when a fibre cement board is used as permanent formwork. The following restrictions have been found and are detailed below:

- The durability of the actual fibre cement boards was not investigated
- Permanent formwork is intended to remain in situ for a long time. For the sake of this research, the permanent formwork's lifespan was constrained by the testing schedules

1.5 Justification for the research

Using permanent formwork removes the consequences relating to re-use as required by temporary formwork. The benefits of permanent formwork may be realised through time and cost savings, a predefined uniform surface finish, and an increased structure lifecycle owing to the protection from deterioration the underlying concrete has from the overlain formwork.

2. Literature review

The purpose of this chapter is to review earlier research relating to the subject of employing fibre cement board as a permanent formwork.

2.1 Formwork

2.1.1 Purpose of formwork

Formwork is used as a temporary container to contain and mould fresh concrete. Concrete is viscous when freshly mixed; hence, it has no load-bearing capacity—the concrete transitions from a vicious state to a solid form through hardening. The solidification of the concrete leads to strength development in the concrete's microstructure. The precision of the moulding activity is essential because once the concrete solidifies, it cannot be remoulded and requires substantial effort to destroy.

Forms can be made from a variety of different materials. Aluminum, steel, plastic, and wood are examples. Each material has qualities that are important in various contexts such as cost, usability, and surface finish. Due to the possibility of creating systems for a single use or a number of uses the formwork's longevity varies as well.

2.1.2 Economics of formwork

Formwork accounts for a considerable proportion of the price of reinforced concrete structures. The cost of formwork, concrete, labour for the concrete work, and labour for the formwork would typically be included in the price of a reinforced concrete construction. A sizable portion of the total cost is attributable to formwork labour costs. According to Hanna (1998), the labour expenses for formwork in traditional cast-in-situ construction vary between 38% and 52% of the casting process, and the total cost of formwork in relation to a structure might range from 40% to 60% of the building's costs.

High labour costs are a result of the difficulty in assembling and dismantling forms. The formwork boards must be assembled, connected, and supported for the concrete to be cast. This renders the process of creating the formwork labour-intensive. The formwork must then be taken apart and re-erected for further use after the concrete has achieved the necessary strength. The process described above, which involves using and re-using formwork, is known as a "formwork cycle." There is not enough data to compare the costs of reusable versus single-use formwork as more research is needed in this area.

2.1.3 Formwork and concrete lifecycles

The construction of reinforced concrete structures relies on formwork. Formwork cycles have a significant impact on the overall project progress because the contractor typically works to minimize the amount of on-site formwork in order to save money.

According to Hanna (1998), the efficiency of formwork operations, and a contractor's ability to recycle through his formwork determines the speed of construction on building projects. Additionally, formwork systems involve extensive shoring to provide the required support.

Figure 2-1 shows how formwork is shored during construction. Hanna (1998) further explains that shoring may limit the progression of certain construction activities due to the system taking up or blocking sections of the construction project. Furthermore, shoring systems can be re-used, leading to contractors re-using shores for subsequent pours, and for additional support after formwork removal.

Figure 2-1: Shoring for concrete and formwork (Peurifoy, R. L., Oberlender, G D., 2011)

The lifecycles of formwork and concrete construction are highly integrated in practice. According to Hanna (1998), the function of formwork is to provide a container that enables the creation of structural parts that correspond to the size and shape specifications established by a designer. The objective of the concrete lifecycle is to produce concrete that satisfies the specifications for strength, durability, and surface texture. Figure 2-2 illustrates how the lifecycles of formwork and concrete construction are interconnected.

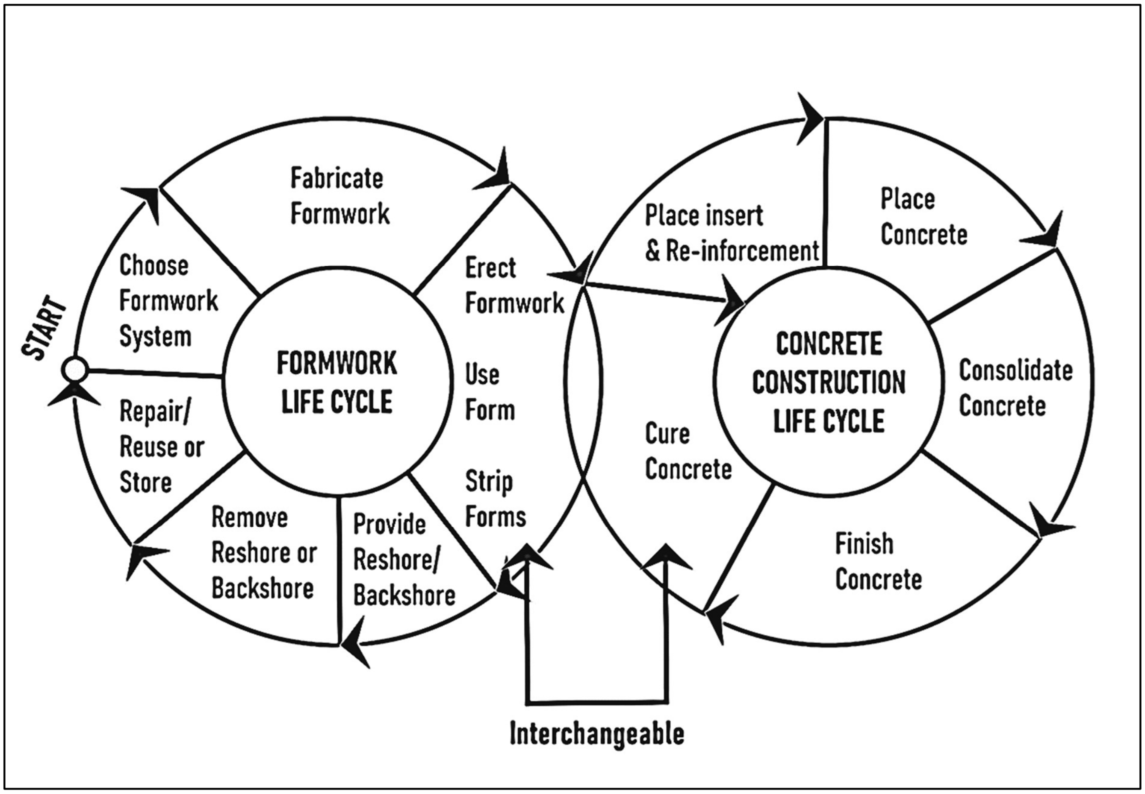


Figure 2-2: Integration between formwork and concrete lifecycles (Hanna, 1998)

The first step in the formwork lifecycle is fabrication. It begins with selecting an acceptable formwork system. Whether a formwork system will be temporary or permanent depends on the choice of the formwork system. Identifying the appropriate bracing, release agents, and formwork material type is also part of the selection process.

The erection process requires the joining, lining up, bracing, and placing of formwork components. This step is crucial because the final shape of the hardened concrete will depend on how precisely the formwork is put together. If the selected release agents are not applied to the formwork during the erection phase, the formwork will bind to the concrete and make the stripping process more challenging since more work will be required to debond the concrete from the forms. According to Hanna (1998), removing the formwork that did not utilize release agents takes more work, and could damage the surface finish of the concrete, necessitating additional repair work.

The installation of the steel reinforcement marks the start of the concrete construction phase. The concrete can be cast or placed into the formwork once the reinforcing has been assembled. The concrete must maintain material consistency throughout the casting and placing process. According to Middel (2009), segregation could happen if material homogeneity is not preserved. Segregation causes a non-even distribution of concrete constituents which causes the cast member's strengths to vary.

Concrete needs to be compacted after placing to release the trapped air. According to Middel (2009), air pockets contribute to the production of voids which affects the durability and strength of the hardened concrete. After the concrete has been compacted, finishing takes place.

Finishing refers to producing a final surface that satisfies both ascetic and practical requirements. Engineers and architects may demand that the surface be either smooth or abrasive depending on the concrete's intended purpose.

The formwork can be removed once the concrete has reached sufficient strength. Stripping or striking is the process of removing the formwork from the concrete. According to Middel (2009) the best time for stripping depends on several variables, including the type of member, the concrete's mix, the temperature, and the curing conditions until the concrete can safely support its weight. Bracing may need to be maintained while it is stripped.

Concrete is exposed to the external environment once the formwork has been removed. Environmental factors can impact how well concrete cures since exterior processes like wind-related evaporation can remove internal water that is necessary for the curing process. The concrete may be protected by curing agents or plastic wrap to cover objects, thereby preventing water from evaporating.

2.1.4 Temporary formwork

Depending on the type of formwork system, temporary formwork is defined as formwork that can be removed after the concrete reaches a specific strength and may be re-used. Temporary formwork systems can be made from a variety of materials. Each material has distinct qualities that may have advantages or disadvantages compared to other systems. All temporary formwork systems abide by the requirement that they are removed and re-used after the concrete has sufficiently hardened. Due to user familiarity and accessibility, temporary formwork systems are the most popular formwork utilised in construction.

Temporary formwork, once removed, reveals the finished concrete surface. The concrete surface finish is dependent on the formwork. Hanna (1998) explains that the surface quality of concrete is dependent on three aspects: the quality of formwork, formwork materials, and workmanship. Defects resulting from poor formwork may manifest in the form of concrete discolouration, stains, and dusting. Poor formwork may also lead to unplanned deformations in the concrete as formwork boards can distort due to repeated use or poor material management.

2.1.5 Permanent formwork

Formwork that remains permanently once the concrete hardens after casting is called permanent formwork. While permanent formwork has several advantages over temporary formwork, the cost is higher because the system cannot be re-used.

If the designer considers the structural characteristics of the permanent formwork, concrete elements can be constructed to benefit from the strength of the permanent formwork. When it does, this is referred to as "participating formwork,". When it does not it is known as "non-participating formwork" (Wrigley, 2001). How the designer approaches the structural and functional needs of the structure will determine whether permanent formwork will participate structurally.

Wrigley (2001) states that permanent formwork provides several benefits when used in construction. These are listed as follows:

- It allows for off-site manufacture in factory conditions which improves product quality
- It eliminates the striking requirements of the formwork which improves production rates
- It removes the programming considerations for the re-use of formwork
- It allows for prompt access to areas and activities that would otherwise have been restricted due to temporary formwork
- It provides a level of protection to the underlying concrete from abrasion the permanent formwork acts as a physical barrier
- It may potentially improve concrete curing and reduce shrinkage cracking by limiting the amount of water that can be drawn from the concrete, but this is dependent on the formwork's material characteristics.

In contrast to a cast concrete surface with defects like honeycombing, air voids, map cracking, etc., defects on permanent formworks can be detected before installation, and the boards can be replaced with defect-free boards. Construction must be carefully done since permanent formwork conceals the concrete beneath, so caution must be given while using it. The underlying concrete is covered, making it harder to spot flaws that might otherwise be visible. Middel (2009) states that faults, such as high void content brought on by inadequate compaction, are not always apparent when employing permanent formwork and advises that activities be carefully monitored to reduce the possibility of defects.

2.1.6 Safety

Formwork operations are inherently dangerous since workers must work at heights with heavy materials which, if improperly installed, may cause injury or death.

Formwork failures can be connected to structural problems during the building process. According to Hanna (1998), formwork failure accounts for more than 50% of structural failures. Such errors may result from:

- Incorrect structural formwork design
- Inadequate shoring
- Improper construction practice
- Inadequate bracing
- Unstable supports
- Incorrect concrete mix design

When workers are required to remove the formwork boards during the stripping process, failures of the formwork frequently occur. If mishandled, these boards could collapse onto workers and cause harm or even death. According to Hanna (1998), formwork failures are a significant cause of accidents and fatalities in the construction sector. In the case of permanent formwork, it is essential that it can be safely left in place for an extended period because de-bonding could result in boards that pose a danger to nearby people.

2.2 Bond strength to permanent formwork

The bonding requirements of permanent formwork to the concrete have not been extensively researched. However, the requirements for the bonding between concrete overlays and substrates and their needs have been studied in the field of concrete repair.

These concrete repair-related factors can be relevant to permanent formwork and its relationship to encased concrete. For comprehension, it was assumed that the permanent formwork would function as the substrate and the cast concrete would be the overlay. However, the bond between permanent formwork and the concrete that has been cast may not be precisely governed by some parameters that affect the bond between concrete repairs and concrete substrates.

2.2.1 Factors affecting bond strength

The stress needed to separate composites at the material interface is bond strength. The connection of a boundary layer between two materials that share an interface can be best described as adhesion. According to Beushausen, Hans & Alexander (2008), adhesion mechanisms between concrete overlays and substrates fall into three groups: chemical bonding, thermodynamic processes, and mechanical interactions.

Although it is acknowledged that it is not the only determining factor, material strength is one of the components that affect bond strength. Bond strength development is based on substrate preparation, material strength, and effective surface area, according to Bissonnette, Vaysburd & von Fay (2012).

The two stages of concrete; namely, the viscous and solid states, have an impact on how the bond's strength develops in concrete repairs. To increase the effective surface area of the contact material that it is being bound to, the concrete can fill open spaces and voids in the viscous condition. The formation of the cement matrix is responsible for the concrete setting and hardening. The strength of the concrete material and, the bond strength increases as the cement matrix develops (Beushausen, 2005).

Evaluating a bond's quality can be challenging because many variables and circumstances affect bond strength. According to Beushausen, Hans & Alexander (2008), it is widely recognised that short-term bond strength is influenced by workmanship quality, and that differential shrinkage is a crucial factor affecting a bond's long-term performance.

The success of concrete overlays is greatly influenced by surface preparation. In the context of permanent formwork, surface preparation is essential since the effectiveness of the bond formation may be affected by the substrate's cleanliness, moisture content, interface roughness, and usage of bonding agents.

Preparing a concrete surface so that a solid and long-lasting bond can form between the parent concrete and overlay materials is known as substrate preparation which is sometimes known as surface preparation. According to Alexander & Beushausen (2009), the preparation's goal should be to create a sound, textured surface devoid of impurities and micro-cracking.

Interface roughness has been found to affect the bond strength of concrete repair materials. This is relevant to permanent formwork as a strong bond to the concrete must exist for the permanent formwork to remain in place. To improve interface roughness, a variety of methods can be applied. The roughening process has a significant impact on how effective the surface roughness is. The optimal roughness, or threshold value of surface roughness, is comparable with a surface that has undergone sandblasting (Silfwerbrand, 1990).

2.3 Transport properties of concrete

The term "transport properties of concrete" describes how particles can move through concrete. As they help to understand the concrete's penetrability, these qualities are particularly relevant in the subject of concrete deterioration.

2.3.1 Permeation

Permeation refers to the movement of fluids through a concrete’s pore structure under an externally applied pressure whilst the pore structure is saturated with the same fluid. Permeability describes the degree to which fluids can permeate through concrete under the conditions described above. Otieno, Alexander & Beushausen (2010) States that permeation depends on the concrete’s micro-structure, moisture condition, material characteristics, and the properties of the fluid used in permeation.

2.3.2 Absorption

Absorption refers to the process whereby a fluid is drawn into a porous, unsaturated material under capillary actions. The extent to which fluids can be drawn into concrete depends on the degree of saturation of the material, and the geometry of the pores. (Otieno, Alexander & Beushausen, 2010) states that the surface of the concrete is where absorption is most significant since capillary action decreases as the concrete depth increases.

Sorptivity measures how quickly a porous substance may absorb water under the influence of capillary action. The size and interconnectivity of the capillaries, as well as the degree of hydration of the outer concrete surface, have an impact on sorptivity.

2.3.3 Diffusion

Diffusion refers to the process whereby a liquid, gas, or ions can move through a porous material under a concentration gradient. Diffusion can occur in concrete that is partially or fully saturated. Diffusion is a key transport mechanism in concrete deterioration, as it is the primary transport function when concrete is in a marine or wet environment.

2.3.4 Migration

Migration is the movement of ionic fluids under the effects of an electric field into a porous material. Otieno, Alexander & Beushausen (2010) states that this mechanism is also referred to as accelerated diffusion as the electric field can be applied and controlled externally. The accelerated diffusive effects are valuable in the laboratory environment as they provide insights into diffusive characteristics that would otherwise only be seen over extended periods.

2.3.5 Combined transport processes

Combination transport mechanisms are when gases, liquids, or ions enter a concrete matrix via different transport processes. According to Ballim, Alexander & Beushausen (2009) more than one transport process is often operating at once as it would be oversimplified to assume otherwise.

Chloride ingress into concrete can be referred to as a combination process, particularly in marine environments. Within a submerged environment, chlorides can enter the concrete through diffusion processes. As the submerged depth increases, the pressure increases proportionally resulting in permeation actions. In an inter-tidal zone, chlorides may enter a concrete matrix at the surface through capillary actions which is considered as an absorption transport process. When the tides rise, the chlorides migrate further into the concrete under diffusive mechanisms. Figure 2-3 shows that along a single concrete element various transport effects may be active.

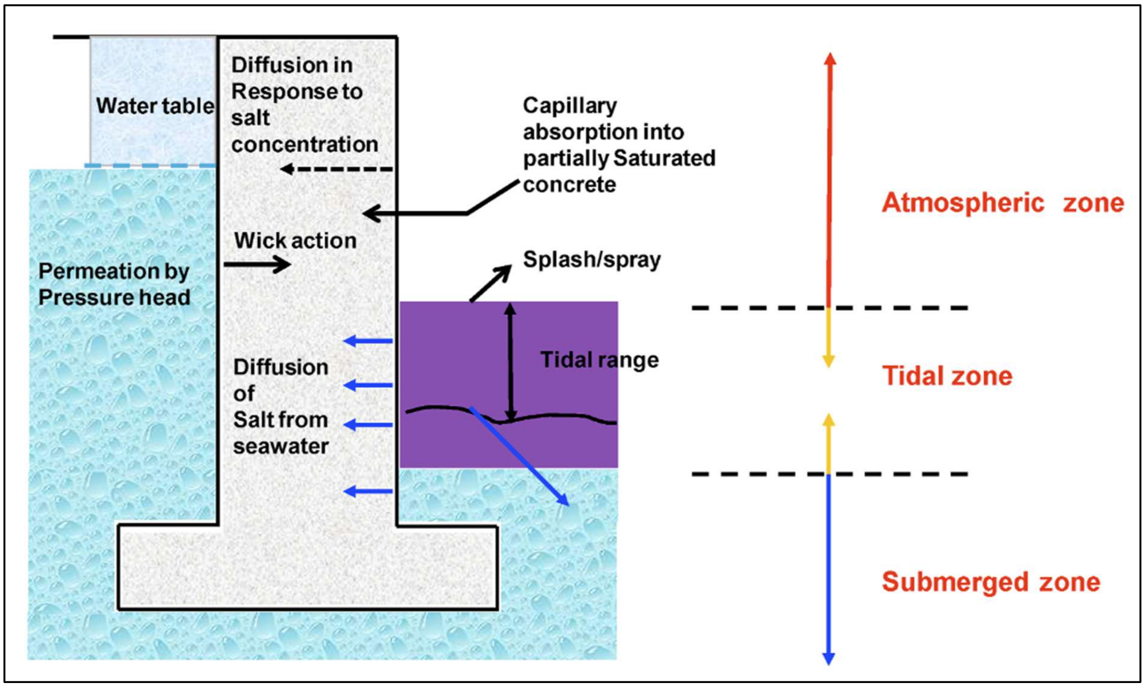


Figure 2-3: Different transport mechanisms in a marine environment (Qu et al., 2021)

2.4 Concrete deterioration

The phenomena of concrete deterioration plague concrete infrastructure. Premature deterioration leads to increased maintenance expenditures and repairs that may have been avoided. It is crucial to understand the reasons for deterioration. This section seeks to go through some of the reasons concrete deteriorates.

2.4.1 Reinforcement corrosion

The most prominent deterioration that develops in reinforced concrete structures is reinforcement corrosion. The steel corrosion process is what leads the reinforcing corrosion related degradation.

The corrosion process is electrochemical producing an anodic site where oxidation takes place, and a cathodic site where reduction takes place. The cathodic site is where the corrosion products form, and the anodic site is where there is a loss of metallic material. According to Andrade (2007) continuity across the metal between the anode and cathode, as well as continuity across the electrolyte, must be present for the electro-chemical process to occur. In reinforcement corrosion, the steel bar serves as the metallic pathway wherein electrons can flow between the anodic and cathodic sites. The electrolyte is provided by the alkaline pore solution and requires water and oxygen to be present. The culmination of all the above conditions allows the following reactions to occur:

$$\text{Anodic: } 2Fe \rightarrow 2Fe^{2+} + 4e^{-}$$

$$\text{Cathodic: } 2H_2O + O_2 + 4e^{-} \rightarrow 4OH^{-}$$

The volume that the steel occupies increases due to the volume of the products of the reaction being larger than that of the steel. This phenomenon induces tensile stresses that can cause the concrete to crack. Concrete cracks result from the concrete's inability to resist these tensile stresses. Increased water contact with the steel is made possible by the concrete's cracking which accelerates the corrosion process even more. Additionally, the corrosion process discolours the concrete, and reduces the cross-sectional area of the steel (Cement & Concrete Institute (South Africa), 2013).

2.4.1.1 Steel passivation

Due to the high alkalinity of the concrete's pore solution, typically above a pH of 12.5, the steel embedded in concrete naturally receives a level of protection. Because it causes the formation of a very thin layer of gamma ferric oxide on the surface of the steel, the steel is protected from contact with harmful ions. Additionally, steel has low reduction potentials at high pH levels, such as those found in concrete, and electrochemical processes can only occur when they are thermodynamically feasible.

2.4.1.2 Carbonation-induced corrosion

Carbonation-induced corrosion is due to the concrete’s exposure to carbon dioxide. This process occurs when carbon dioxide, which is present in the atmosphere, enters a concrete’s pore structure and reacts with calcium hydroxide. The reaction has a final product of calcium carbonate, but carbonic acid is formed during the process. The pH of the concrete is lowered by the carbonic acid to below a pH of 8, where passivation can no longer function making the reinforcing steel vulnerable to corrosion. Steel corrosion takes place if there is water and oxygen present. Due to the need for ambient carbon dioxide to reach the concrete, carbonation is often a protracted process. Carbonation-induced corrosion occurs uniformly across the reinforcement as carbonation appears as a front that steadily advances through the concrete.

2.4.1.3 Chloride induced corrosion

Chloride-induced corrosion, which is more aggressive than carbonation-induced corrosion, is prevalent in marine and coastal environments. Usually, chlorides penetrate the concrete in one of two ways: firstly, when they are present in the materials used in the mixing of the concrete, and secondly, when they penetrate the concrete.

Penetration occurs by means of water-filled concrete pores that allow chloride ions to enter the concrete's micro-structure. The chlorides, enter the concrete through absorption, permeation, and diffusion and are generally present in salt waters and marine mists. Chlorides that have reached the level of the steel cause localised disruptions in the passivation layer protecting the steel. Andrade (2007) explains that the disruption is caused by localized acidification of the steel which results in the formation of iron hydroxides. During the corrosion reaction, no chlorides are consumed. These chlorides, therefore, remain free to induce further corrosion.

Chlorides that have penetrated to the steel's level cause localized disruptions in the passivation layer that protects the steel. According to Andrade (2007), the disruption is brought on by a localized acidification of the steel which leads to the removal of the passivation layer (often termed depassivation). Figure 2-4 shows the effects of chloride-induced corrosion on a reinforced concrete member in a coastal environment with high chloride exposure.

Figure 2-4: Chloride-induced corrosion of a reinforced concrete member in a coastal environment

Concrete has the ability to bind a certain number of chlorides, and these bound chlorides do not cause corrosion. The number of chlorides that can be bound to concrete is known as the chloride threshold. Andrade (2007) explains that the chloride threshold value is not an exact value as it is dependent on several factors, these are:

- Availability of oxygen
- Moisture content in the concrete's pores
- The type of binder used
- Steel type and surface finish of the concrete
- Curing and compaction of the concrete
- The use of blending agents and their chemical compositions

The aforementioned parameters and their wide-ranging variability make it challenging for designers to specify an exact chloride threshold value per a specific concrete mix. According to Mahima et al. (2018), various researchers have found chloride threshold values that range from 0.1% to 1.2% mass of cement. In South Africa, the chloride threshold percentage by mass of cement has been set as 0.4% chlorides by mass of cement. The understanding is that any chlorides that are above this value will be free to cause reinforcement corrosion.

2.4.2 Alkali-silica reaction

When reactive silicas are exposed to moisture, they form an expansive silica gel. This reaction is known as alkali-silica reaction (ASR). Reactive silicas are present in particular aggregates used in concrete production. Aggregates with reactive silicas do not usually show deterioration because specific conditions must be met before the expanding silica gel forms.

Oberholster (2009) explains that deleterious cracking by ASR can only occur if the following conditions are met:

- Sufficient alkalinity must be present in the concrete pore solution,
- There must be an adequate amount of reactive silica must be present in the aggregate,
- Environmental conditions must be conducive for the reaction to occur which in the case of ASR, moisture must be present.

The expansive silica gel forms around the aggregates once the above conditions are satisfied. Figure 2-5 shows the formation of silica gel around aggregates in concrete. The gel causes tensile forces to develop within the concrete matrix and results in the cracking of the concrete. Oberholster (2009) explains that cracking occurs once the tensile forces induced by the silica gel exceed the tensile strength of the concrete.

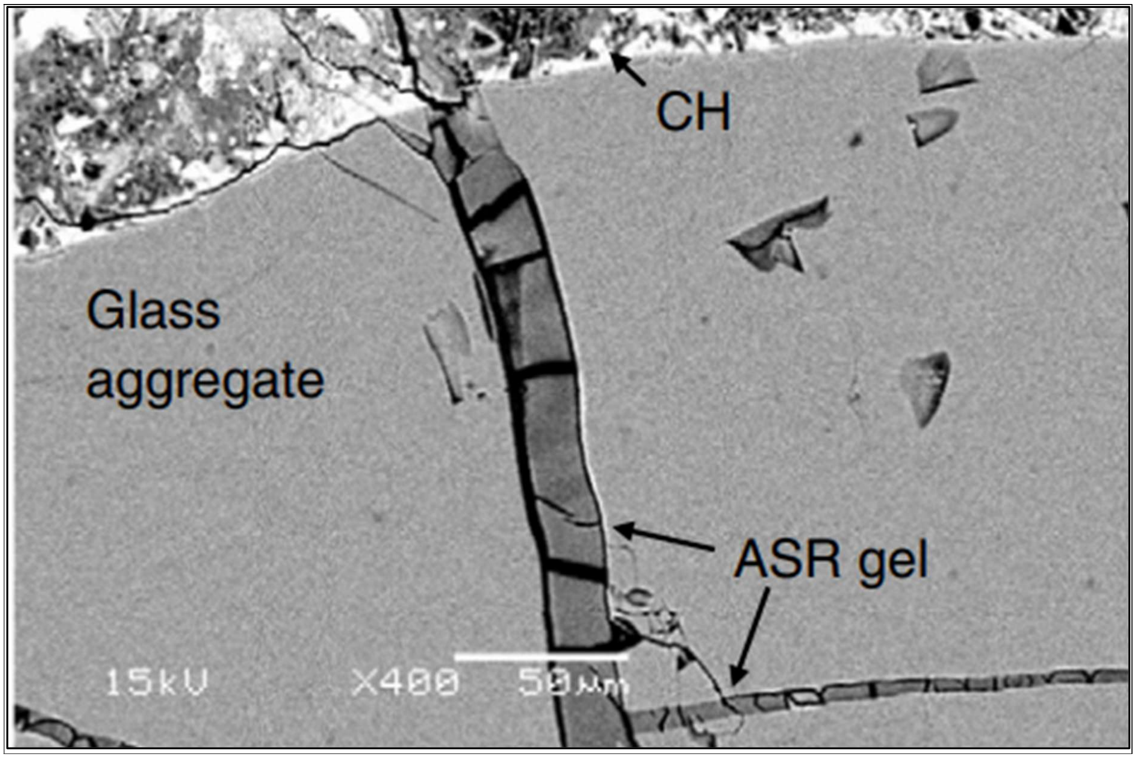


Figure 2-5: Deleterious silica gel formation around aggregates (Rajabipour et al., 2015)

The presence of moisture is a key requirement for the formation of ASR. If permanent formworks are used, a barrier is created to restrict the ingress and availability of moisture in the concrete, thus preventing the reaction from occurring.

2.4.3 Chemical attack

There are various types of chemical attacks on concrete, such as acid and soft water attacks. The chemistry involved is different in these types of attack is different, but the eventual outcome is the disintegration of the cement matrix. Degradation of the cement matrix during chemical attack of the concrete exposes the aggregates, which are then dislodged from the concrete by abrasion. Figure 2-6 shows the degradation of the cement matrix as the aggregates are exposed due to the leaching of calcium compounds from the cement.

The significance of fibre cement permanent formwork in this section is that it covers the concrete and thus prevents direct contact between the chemicals and the underlying concrete. Fibre concrete will deteriorate in the same manner as the underlying concrete, but as it serves as a cladding, it can be replaced when necessary, leaving the underlying concrete undamaged.

Figure 2-6: Concrete cube exposed to sulphuric acid for 84 days (Kumar & Gupta, 2015)

2.5 Durability of concrete

Concrete structures' capacity to function for the duration of their design lives, and longer, depends on how durable it is. Concretes’ durability relates to its ability to withstand external environmental factors that could otherwise lead to deterioration and determines how long it will perform.

2.5.1 Factors that improve concrete durability

It is essential to understand how to improve concrete durability because it directly affects the longevity of a structure.

2.5.1.1 Concrete compaction

The removal of the entrapped air in concrete is done through the process of compaction and can only be done whilst concrete is in a viscous state. The concrete's density, strength, and impenetrability are all improved by releasing the trapped air. According to Kellerman (2009), compaction boosts concrete strength, and provides durability benefits by reducing penetrability. Conversely, the strength of concrete declines by roughly 5%-6% for every 1% extra voids.

2.5.1.2 Curing

Curing describes procedures that stimulate the cement's hydration reactions. It is essential for the concrete structures’ long-term strength and durability as improperly cured concrete is weaker and more permeable than properly cured concrete.

The conditions for the cement hydration reaction are promoted by the curing process, which regulates the temperature and water movement through the concrete. Cement hydration reactions occur when water and cement chemically mix to form a cement paste. According to Perrie (2009), only water-filled areas can form cement paste in fresh concrete. Concrete stiffens and later hardens because of the creation of the cement-paste and its subsequent hydration. The cement paste is primarily in gel form during hardening, and is frequently referred to as hardened cement paste. According to Perrie (2009), the hardened cement paste during concrete hardening compromises calcium hydroxide crystals and unhydrated cement. The gel is not entirely solid in this form because one-third of it is made up of tiny pores. These pores are not large enough to negatively affect the concretes penetrability. The original water-filled spaces gradually fill with cement gel and forms a matrix structure as the hydration reaction progresses. The interconnectivity of the initial water-filled system is reduced as the cement gel moves through initially water-filled spaces.

The strength and durability of concrete is influenced by how much cement hydration can take place. The porosity of the concrete and hardened cement paste both contribute significantly to the strength of concrete. The relationship between porosity and the extent of the development of the hardened cement paste’s micro-structure influences the density of the concrete. Although the objective is to reduce the porosity of the concrete as much as possible, even in ideal circumstances, concrete normally retains a porosity of approximately 16%.

Within the context of concrete durability, the primary focus is on the impenetrability of the surface concrete. A denser cement micro-structure makes it difficult for ions to move through the concrete. According to Gowripalan et al. (1990), concrete that has been properly cured has less porosity, permeability, and absorption characteristics than poorly cured concrete, making it more resistant to the penetration by deleterious ions. The amount of internal water, as defined by the water-to-cement ratio, is sufficient for curing and further saturation of the concrete is not necessary. However, when the concrete's internal water is removed, problems with hydration arise. Fresh concrete is particularly vulnerable to water loss. Water loss is typically caused by evaporative processes such as heat and windy conditions. Whilst the loss of water decreases the curing effect of the concrete, it can also cause shrinkage cracking. The presence of shrinkage cracks can result in accelerated deterioration of the concrete as harmful ions can penetrate deeper with little to no resistance from the concrete.

There are several different curing techniques, and they all rely on maintaining the internal mixing water to sustain the hydration of the cement. The application of membrane-forming curing chemicals, which restricts the removal of water from the concrete, is a typical curing approach. Wet curing is the process of preventing moisture loss by creating a moist or wet environment. This technique also helps to keep a constant temperature along the concrete's surface. Plastic sheets or impervious papers are also frequently used as impermeable coverings for concrete to retain internal moisture, while leaving temporary forms in place until the concrete is adequately cured is another way of curing.

In a manner comparable to temporary formwork, the permanent formwork preserves its ability to prevent concrete losing water throughout curing. The optimal cured strength and impenetrability could be achieved if the permanent formwork can provide an environment that is suitable for curing concrete. Another advantage is that a contractor can continue with other activities without being concerned about the concrete's incorrect curing and having to commit resources to ensure that the curing is achieved.

2.5.1.3 Cover to reinforcement

The distance between the concrete's surface and the reinforcing steel is referred to as the "cover to reinforcement" or "concrete cover". This is the depth necessary for hazardous ions to penetrate the concrete’s surface to reach the reinforcing steel, which is of interest in the context of concrete durability.

The concrete cover serves as a barrier to protect the concrete. A deeper cover depth is preferred from a durability perspective since it increases the concrete's resistance to deterioration. SANS 10100-2 provides criteria for concrete cover depending on how aggressive the environment is, and if permanent formwork is present. Increased concrete cover adds additional weight to the structure, which would increase costs because the additional weight would need to be taken into account in the design of the structure. Concrete cover should be optimized to account for cost, environmental exposure conditions, and structural requirements according to Kepler, Darwin, & Locke Jr (2000). While protecting against the entry of hazardous ions has been a key area of study, concrete cover also affects fire and impact resistance. Impact resistance is particularly crucial because if damage from impacts reaches the level of the reinforcing steel, the structure could collapse. The concrete cover functions as a barrier, dissipating impact force.

The effectiveness of concrete cover is dependent on the quality of concrete used and the presence of cracking. In instances where concrete cover is sufficiently specified, but the concrete is of poor quality possibly due to poor compaction or curing, the protection provided by the concrete cover is diminished. The presence of cracks makes the penetration of harmful ions into the concrete easier, regardless of concrete quality, as the harmful ions effectively bypass the cement matrix in areas with cracks.

Barrier systems have been utilized to provide additional protection in concretes that lack or are incapable of having sufficient cover. Examples of such systems include concrete overlays, water-resistant membranes, and concrete sealants. While all these techniques apply to already-built structures, the same principle can be used for permanent formwork systems for new structures.

In the context of durability, permanent formwork systems are physical barriers that prevent harmful ions from entering the concrete. They also have a defined thickness, increasing the penetration depth necessary for the ions to reach the reinforcing steel. The protection provided by permanent formwork could reduce the minimum cover requirements, but this is dependent on the exposure conditions, and the aggressivity of the environment. Good judgement should be applied in these scenarios. SANS 10100-2 makes provision for the use of permanent formwork by decreasing the cover requirements provided that the permanent formwork is not susceptible to weathering or corrosion. Guidance is however not provided in the code on materials that adhere to these requirements.

2.5.2 Durability index testing methods

The durability index test methods are used to quantify concrete durability. These test procedures are used to quantify the concrete's performance in terms of durability. According to Ballim, Alexander & Beushausen (2009), the oxygen permeability test, the water sorptivity test, and the chloride conductivity test are all compromised by the durability index test methods and are connected to the transport mechanisms that cause concrete to deteriorate. The tests are sensitive to conditions such as curing and compaction.

2.6 Fibre cement

The literature that is currently available on fibre cement is discussed in this section.

2.6.1 Background

Modern society has developed numerous fibre cement composites made of a variety of fibre components. The widely acknowledged weakness of concrete is its poor tensile strength. This is addressed by adding components capable of withstanding tensile stresses which results in better-performing material.

Simple mud/dung mixtures to more sophisticated modern cement-based mixes are all examples of fibre-based mixtures. Fibre cement has a wide range of qualities. According to ACI 544.1R-96, fibres in cement’s have been proven to improve flexural toughness, crack resistance, and flexural fatigue.

2.6.2 Fibre types

A wide variety of fibres are available. Fibres' constituting materials can be divided into four basic categories: steel, glass, synthetic, and natural. Each material has a varied set of material qualities depending on its categories and subcategories.

Steel fibre cements consist of cements that contains steel fibres. The steel fibres within the cement matrix provide additional tensile capacity as tensile failure is only realized if the steel fibres break or are pulled out of the cement.

Glass fibres have been utilized in fibre cements, but they weren't suitable for long-term applications since the alkalinity of the cement caused them to deteriorate, which led to a loss of strength over a relatively short time. The creation of alkali-resistant glass fibres solved the deterioration problems. The inclusion of zirconia, according to ACI 544.1R-96, increased the glass fibres’ resilience to the alkalinity of the cement.

Synthetic fibres consist of materials, such as carbon, nylon, polyester, polyethylene, polypropylene, aramid, and acrylic. Historically, these fibres have emanated from the textile and petrochemical sectors.

Naturally occurring fibres consist of processed or unprocessed fibres. Unprocessed natural fibres can be obtained from a variety of plants, including hemp and bamboo. These fibres normally come from the plant stems and require only a minimal amount of processing before use. Because of the ease of extraction and processing, these fibres are widely available. Natural fibres that have undergone processing to enhance their qualities are referred to as processes natural fibres. ACI 544.1R-96 explains that processed natural fibres are extracted from wood using chemical treatments.

2.6.3 Manufacturing of fibre cement

Glass fibre cements can be produced in one of two methods; these are through a spray-up process or premixing. In the spray-up technique, chopped glass fibres are incorporated into a slurry of sand and cement. The slurry is then sprayed into moulds where it hardens into the desired form. Spraying is carried out in 4-6 mm thick layers with each layer being roller compacted. Cement, glass fibres, water, and admixtures are used in the premixing technique. Standard concrete mixing equipment can be used to combine this mix, but caution must be exercised to prevent damage to the glass fibres. Vibration is used to compact premixed cement mixture. According to ACI 544.1R-96, moulding is frequently utilized to create unique cladding elements, and can be produced through press-moulding, extrusion, or slip forming.

For synthetic fibre cements, batch mixing is frequently employed. Fibres are added directly to the wet mix during batch mixing. Because the synthetic fibres tend to cluster together, it is necessary to stimulate the mixture to ensure uniform dispersion of the fibres. There are several different methods for placing batched fibre cement, including casting, pumping, shot-creting, and plastering.

2.6.4 Fibre cement properties

In comparison to cements, fibres have higher tensile properties. Unreinforced concrete's low tensile strength is compensated for by the high tensile strengths of fibres, which increases the material's overall strength.

When steel fibres are used in fibre cement the high alkalinity of the cement matrix prevents corrosion of steel fibres as they are embedded in concrete. Although the pull-out of the fibres may be a problem, the binding to the cement can be improved by roughening the fibres' surface and improving the mechanical anchoring. According to ACI 544.1R-96, stainless steel fibres should be utilized in potentially corrosive environments as they offer improved corrosion resistance over plain steel fibres.

The 28-day Proportional Elastic Limit (PEL) of glass fibre cements governs their use. The PEL is a primary consideration as any stresses beyond this limit causes the material to crack. Cracking of glass fibre cement is considered a serviceability failure as the material has a significant stress and strain capacity exceeding the PEL. The capacity for stress and strain exceeding the PEL is a result of fibre pull-out is stated in ACI 544.1R-96. Glass fibres suffer pull-out when stress loading produces cracks. The pull-out action of the glass fibres from the cement matrix creates friction which leads to the development of load resistance. Glass fibres have been discovered to have decreased tensile and flexural capabilities over time. The tensile strength is reported to be reduced by around 60% when they age and are exposed to the external environment.

As synthetic fibre cements consist of a wide variety of fibres, it also offers a wide range of properties. While having good dimensional stability, and a weight-to-strength ratio of five times that of steel, aramid fibres are expensive and have never been widely adopted. Carbon fibres are resistant to most substances, and have high strengths and elastic modulus. Widely employed in the textile sector, nylon fibres have good elastic recovery and stability at elevated temperatures, but they also tend to absorb water.

2.6.5 Applications

Cements with steel fibres has been successfully used in a broad range of environments. The distribution of their fibres enables them to withstand the deteriorating effects of cavitation and erosion. Steel fibre cements have been utilized in dam repairs, and have also been used to pave highways and repair concrete bridge decks. Additionally, they have been utilized as Dolosse to disperse wave energies in coastal zones.

Cast-in-place and precast applications are the two main uses of synthetic fibre cements. As ACI 544.1R-96 explains, synthetic fibre cements with carbon fibres have been used in a variety of applications, including the construction of curtain walls, free-access flooring, and structural repairs. The applications are, however, limited because using carbon fibres come at a high cost, but this technology has the potential to create more slender concrete elements. Both nylon and polypropylene fibre cements are primarily utilized in non-load-bearing components and have seen limited adoption.

Although Glass fibre cements have found uses in various areas, architectural and structural components have seen the most widespread application. According to ACI 544.1R-96, 80% of Glass fibre cements have been utilized in architectural and structural components, but usage has also been documented in agricultural sectors, asbestos replacement, fire protection systems, marine application, street furniture, and containment.

There have been numerous applications for fibre cements as formwork. According to ACI 544.1R-96, fibre cements have been used as both temporary and permanent formworks. Although these applications were initially linked to bridge construction, they have since expanded to include foundation construction, sewer rehabilitations, and building construction. Figure 2-7 shows a worker preparing a fibre cement permanent formwork for the construction of a bridge deck. By designing the formwork systems to be non-participatory (non-load bearing), the fibre cements act as a form of cladding once the underlying concrete develops load-bearing ability making the glass fibre cements' strength deterioration with age and exposure irrelevant to structural capacity (Bank et al., 2009).

Figure 2-7: Fibre cement boards used a non-participating formwork (Malla et al., 2007)

2.7 Summary of literature

Fresh concrete is moulded in formwork that serves as a container. The formwork is typically removed and reused for additional moulding operations once the encased concrete has hardened and gained adequate strength. Formwork that is used and reused is referred to as temporary formwork. Conversely, formwork that remains in place permanently after moulding is referred to as permanent formwork. The advantage of permanent formwork over temporary formwork is that the forms do not need to be removed and reused after casting, thus saving costs. Instead, they stay in place and become a part of the final structure.

The permanent adherence of the formwork to the structure after casting is a criterion for permanent formwork. There is little research on the bonding characteristics of cement-based permanent forms to concrete structures. However, some aspects influencing the bond performance could be related to the field of concrete repair, where the formwork would serve as the substrate and the fresh concrete as the overlay. The application of good surface preparation was viewed as one of the various aspects that could increase the likelihood of a successful bond formation.

Concrete deterioration is a problem for concrete infrastructure as it reduces the service life of a structure. Deleterious substances that penetrate the concrete are the primary cause of concrete deterioration. The transport mechanisms of permeation, absorption, diffusion, and migration govern the movement of these substances through concrete. Penetration may be affected by multiple transport processes operating in combination with one another. The most prevalent type of concrete deterioration that can be observed in structures is reinforcement corrosion. The deterioration is brought on by the tensile forces that steel oxidation products exert on the concrete, which result in cracking of the concrete and a reduction in the reinforcing steels cross-section. Chloride attack is a form of reinforcement corrosion that is particularly severe and prevalent in marine environments.

The ability of a structure to withstand its environment is referred to in structural concrete as concrete durability. The construction of long-lasting structures is facilitated by concrete durability design. The usage of cover, which works as a protective barrier for the reinforcing steel, increases the concrete's durability. Another crucial area is curing as this ensures that there is sufficient water for the formulation of a dense cement matrix. The denser the cement matrix, the more resistant the concrete is to the penetration of deleterious ions. Numerous methods exist for curing concrete. The use of formwork by keeping it in place is a topic of interest for this study since curing will continue if water is present. The durability index test methods are tests used to quantify concrete durability for structures.

Fibre cements are substances that incorporate fibres into a cement matrix. These materials can be produced in a variety of methods including batch mixing, premixing, and spraying. The flexural and tensile strengths of concrete have been observed to increase with use. The use of these materials has been reported in a diverse range of industries, including construction, agriculture, marine, and safety. Fibre cements have also been utilized successfully as permanent formworks for sewer systems, buildings, and bridges.

3. Methodology

This section explains how the fibre cement boards were tested for curing efficiency, protective support against chloride ingress, and shear bond strength to concrete to evaluate whether they could be utilised as permanent formwork.

In the context of this study, curing efficiency refers to how well concrete cures under a fibre cement board as opposed to when it is exposed. Chloride ingress protection was selected because chloride-induced reinforcement corrosion is the most aggressive type of concrete deterioration. A significant proportion of the world's population and infrastructure are situated in regions that are influenced by coastal processes making this type of corrosion a global issue. These coastal processes disperse chlorides into concrete infrastructure causing the structures to deteriorate. If the fibre cement boards can inhibit chlorides from penetrating concrete, they may be a useful tool in extending the lifespan of infrastructure. The shear bond strength performance was utilized to determine if the fibre cement board would remain in place as a permanent formwork.

In order to create the fibre-cement-board/concrete composite specimens (also known as composite specimens), two concrete mixes were cast against the fibre cement boards. Another set of control companion specimens were also created without the boards (also known as exposed specimens). The concrete mixes were compacted differently with one using vibration compaction (also known as good compaction), and the other using hand compaction (also known as poor compaction).

Since the water/binder ratio (w/b) affects the strength of concrete, a mix of 0.45 w/b and 0.8 w/b was used. The strength of concrete is affected by the water binder ratio - the mixes used were 0.45 w/b and 0.8 w/b. The 0.45 w/b mix had a higher binder content and therefore would have a higher strength than the 0.8 w/b mix. Furthermore, vibration compaction was used for the 0.45 w/b mix and hand compaction was used for the 0.8 w/b mix. For removing air from freshly poured concrete, vibration compaction was utilized since it was a superior technique than hand compaction; the opposite is true for hand compaction.

The parameters were chosen to ensure that the 0.45 w/b mix reflected good-quality concrete with good on-site workmanship and quality controls whilst the 0.8 w/b represented poor-quality concrete with subpar workmanship and controls. The parameters utilised are shown in Table 3-1 below.

Table 3-1: Parameters utilised to confirm the problem statement

0.45 Water Binder Mix		**0.8 Water Binder Mix**	
Composite	**Exposed**	**Composite**	**Exposed**
Good Compaction	Good Compaction	Poor Compaction	Poor Compaction

The performance of the durability index, bulk diffusion, and shear bond strength were all evaluated using the four parameters shown in Table 3-1. Compressive strength tests were used to confirm the concrete strengths at 28 days.

3.1 Preparation of samples

The preparation process for the samples used to test the bonding strength and curing efficiency of fibre cement board is covered in this section.

3.1.1 Concrete mixes

The concrete mix designs were produced, and modifications to the initial mixes were made to achieve the desired concrete characteristics. The experimental approach used two concrete mixes with different methods of compactions and workability. Table 3-2 represents the mix design details for the relevant concrete mixes.

Table 3-2: Mix designs used for the concrete specimens

Mix constituents	**Quantity kg / m^3**	
	0.45 Water Binder Mix	**0.8 Water Binder Mix**
19 mm Greywacke stone	1000	925
Crusher dust	362	550
Dune sand	362	550
Water	210	190
CEM II/A-L 42.5N	462	237.5
Compressive strength (28 days)	50.7 MPa	22.2 MPa

The fine aggregate portion of the mix was selected with a 50/50 combination of dune sand and crusher dust. This was done to improve the fine aggregate grading for the concrete, and to reduce the likelihood of excessive bleeding occurring in the fresh concrete. Based on the water binder requirements, as well as the water demand requirements of the mixes for the specified slumps, the water content was selected. Due to the use of 19 mm stone, no adjustments were required for the coarse aggregate.

SANS 5862 was used to perform slump testing. For the 0.45 w/b mix, a slump of 80 mm was obtained while for the 0.8 w/b mix, a slump of 35 mm was obtained. The first mix, which was vibrator compacted, had a water binder ratio of 0.45. The second mix, which was hand compacted, had a water binder ratio of 0.8. The compressive strengths of the mixes were tested at 28 days, as per SANS 5863, to confirm that the mixes achieved the target strengths. The detailed results of these tests can be found in Appendix 8.2.

3.1.2 Fibre Boards

The fibre boards used were commercially available processed-natural fibre cement boards. The material information of the fibre boards is shown in Table 3-3.

Table 3-3: Fibre cement board material information

Material Parameter	Unit	Value (Test method)
Thickness dimension	mm	15
Density	kg/m^3	1500
pH	-	10-12.5
Compressive strength along the grain	MPa	15.21 (ASTM 1037)
Compressive strength across the grain	MPa	20.61 (ASTM 1037)
Youngs Modulus	MPa	7747

3.1.3 Composite specimens

The composite specimens were made of concrete and fibre cement boards. The fibre cement boards were divided into smaller pieces that matched the existing cubic moulds. The boards were sandblasted using iron shavings to roughen the surface and increased the likelihood of a successful bond forming. The use of iron shavings to sandblast is not the conventional method of roughening the surface but was used due to the availability of the equipment. Using a pressured sandblaster, 0.3 mm-sized particles of iron shavings grit were blasted on the boards. Figure 3-1 shows the sandblasting equipment used to increase the surface roughness of the panels. All sandblasted boards were consistently roughened during the sandblasting process. Previous research by Moser (2019) demonstrated that the fibre cement boards de-bonded before testing without prior surface roughening which served as the foundation for this methodology. While surface roughening was not the focus of this study, different surface roughening techniques and their effects on the bond strength performance of fibre cement boards could be a topic for further investigation.

Figure 3-1: Sandblasting machine used to improve fibre cement boards surface roughness

The concrete cube moulds utilised have dimensions of 100x100x100 mm and 150x150x150 mm. On a vertical face of the cubic mould, fibre cement boards were placed. This method was utilised to replicate how the boards would be used as permanent formwork in practice. Following the batching and mixing processes, the concrete was poured into the moulds and compacted as explained in Section 3.1.1. The cast concrete composite specimens in the cubic moulds are shown in Figure 3-2.

Figure 3-2: Composite specimens with the concrete cast against the fibre cement boards in the cubic moulds.

After 24 hours of setting, the exposed and composite specimens were removed from the cubic moulds. To ensure consistent curing on the exposed concrete faces through the preservation of moisture, the stripped specimens were subsequently wrapped on all concrete faces with a synthetic wrap for seven days to simulate site curing conditions. The curing specimens are depicted in Figure 3-3. The synthetic wrap was taken off after seven days, and the concrete samples were given an additional 21 days to cure. To achieve uniform curing, the specimens were placed in a room with a controlled humidity of 65±5% RH and a temperature of 23±1ºC.

Figure 3-3: Specimens during 7-day curing.

3.2 Test methods

3.2.1 Durability index tests

The 2017 Durability Index handbook was followed when testing the durability index. The Durability index test suite consists of three tests: the oxygen permeability test, the water sorptivity test, and the chloride conductivity test.

The durability index tests are correlated to the concrete's transport mechanisms and provide information on how effectively ions can penetrate the concrete. The tests concentrate on ionic diffusion, water absorption, and gaseous permeation as transport processes. These test procedures are sensitive to the concrete's curing and exterior deterioration processes. According to Ballim, Alexander & Beushausen (2009), the tests are sensitive to elements that affect the durability such as the type of material used, the construction processes, and environmental factors.

Since the fibre cement board was not equivalent to the underlain concrete, it was a challenge when performing the durability index tests on the composite specimens as was discovered by Moser (2019). In his tests, he discovered that the fibre cement board had an oxygen permeability index (OPI) of 9.45 which is categorised as a concrete with poor durability. Thus, only the underlying concrete was tested to assess the curing effectiveness provided by the permanent formwork placed over the concrete for the curing period.

The principles outlined by Alexander, Mackechnie & Ballim (1999) were used to interpret the results. Table 3-4 displays the standards for concrete's durability performance. According to Table 3-4, declining durability class values reflect ascending durability class for both sorptivity and conductivity, whereas ascending OPI values reflect ascending durability class.

Table 3-4: Durability classifications according to index values (Alexander, Mackechnie & Ballim, 1999)

Durability Class	OPI (log scale)	Sorptivity (mm/h$^{0.5}$)	Conductivity (mS/cm)
Excellent	>10	<6	<0.75
Good	9.5 – 10	6 – 10	0.75 – 1.50
Poor	9.0 – 9.5	10 – 15	1.50 – 2.50
Very Poor	<9.0	>15	>2.50

3.2.1.1 Oxygen Permeability test

The oxygen permeability test evaluates the concrete's micro and macro structures at its surface. The test makes use of a falling head permeameter to let oxygen pass through a concrete disk of a specific size. Over a predetermined period, the rate of oxygen decomposition is measured. The outcomes are utilised to determine the OPI value. A better-quality concrete will have a higher OPI value. Cracks and voids affect the oxygen permeability test as they invalidate the test. The test helps to evaluate the interconnectivity of the pore structure (Ballim, Alexander & Beushausen, 2009).

The OPI test preparation had cylinders cored from the 100 mm concrete and composite cubes to a diameter of 70 mm. The cubes were then cut into slices that were 30 mm thick. The samples underwent conditioning by being kept in a 50°C oven for seven days, followed by two hours in a desiccator. After being taken out of the desiccator, the samples' thicknesses and diameters were measured. The samples were placed into airtight cylinders pressurized at 100 kPa using oxygen. After pressurization, the samples were left for six hours while an electronic data logger recorded the decaying oxygen pressures. An assessment spreadsheet, which calculated the OPI values for the specimens, was updated with the data-logged values.

3.2.1.2 Water sorptivity test

The water sorptivity test is a measurement of the concrete's porosity. The test does not reveal how quickly the concrete will absorb water. (Ballim, Alexander, and Beushausen, 2009) advocate that the test is sensitive to the degree of surface concrete curing.

OPI test specimens are acceptable for use in the test as per the durability index manual 2017. Concrete samples were placed in a few millimetres of calcium hydroxide solution as part of the test procedure. To assess the porosity of the concrete, the samples were weighed at regular intervals after being vacuum-saturated and weighed again. The weighted measurements were plotted against the square root of time, with the sorptivity value being the line's slope (Ballim, Alexander & Beushausen, 2009).

3.2.1.3 Chloride conductivity test

The chloride conductivity test provides insight into a concrete specimen's diffusion properties. Under normal circumstances, diffusion is a slow process that can take years to produce the necessary results. Applying a potential difference stimulates the flow of ions into a sample, and can accelerate the diffusion process. Measurements can be captured over a comparatively short time. The chloride conductivity test, which encompasses accelerated diffusion, is sensitive to water binder ratios, binder types, and concrete curing conditions (Ballim, Alexander & Beushausen, 2009).

The preparation of samples followed the same procedures as those outlined in Section 3.2.1.1. Following preparation, samples were vacuum-saturated in a 5 M sodium chloride solution for 24 hours. The samples were then placed into a chloride conductivity cell where a 10 V potential difference was applied. The measured current flowing through the concrete samples was used to determine the chloride conductivity (Ballim, Alexander & Beushausen, 2009).

3.2.2 Interface shear bond test

The interface shear bond test was based on the modified guillotine test developed by Beushausen (2005). The thickness of the fibre cement boards was considered when further modifying the guillotine test. Figure 3-4 depicts how the composite specimen was set up and loaded for the modified guillotine test. The force distributions were calculated using the balance of force method. A bending stress would be created at the interface due to the test alteration. The eccentricity of the load results in bending stresses at the bond interface. However, since the eccentricity of the loading application would be close to the bond interface, the bending stresses were considered negligible.

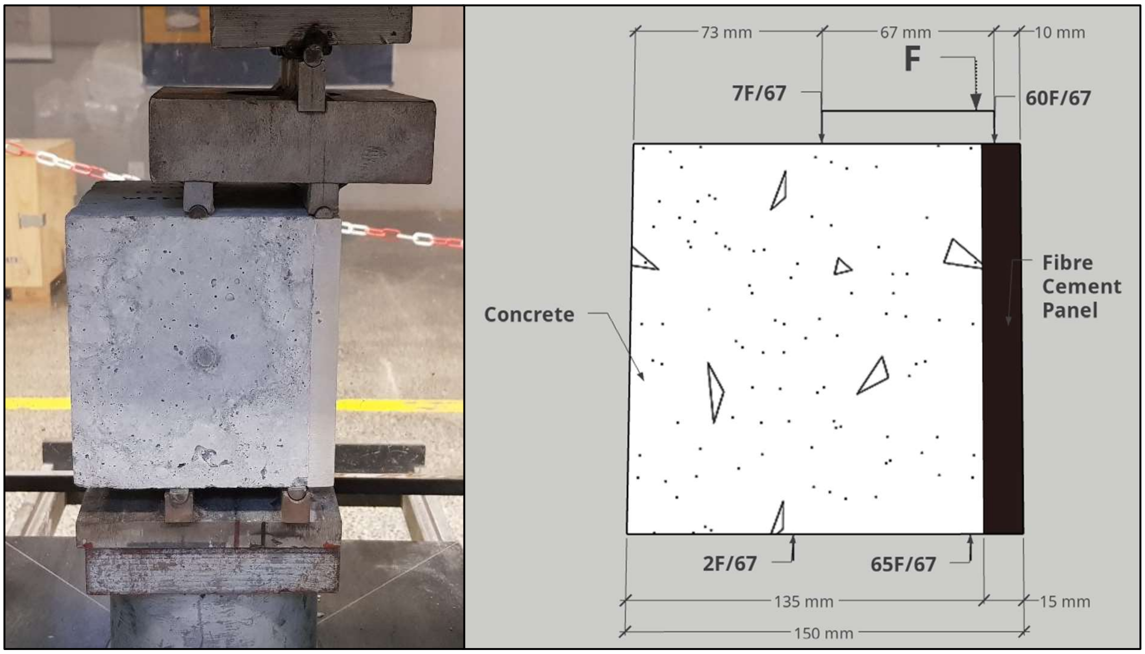


Figure 3-4: Shear bond strength test schematic with applied forces

One of three failure scenarios should be caused by the shear forces generated at the interface. Concrete failure is mode 1. The failure plane in this scenario was in the concrete specimen, and the fibre cement board and interface remained unharmed. Failure of this kind is unlikely because concrete is the material with the highest strength in the test. However, failure may be an indication of improper apparatus setup. Failure of the fibre cement board is mode 2. The fibre cement board is penetrated by the failure plane in this method. Since the interface was anticipated to be the compound specimen's weakest plane, this failure mode was likewise improbable. Failure at the interface was considered the most likely mode of failure and is noted as mode 3. Mode 3 should demonstrate the shear strength of the bond between the materials at the interface.

3.2.3 Bulk diffusion test

The chloride concentrations in the composite and concrete specimens at different levels were determined using the bulk diffusion test technique as per ASTM C1556. The bulk diffusion test is the principal test method that serves as a reference for all chloride-determining methods.

Composite and exposed samples were cast for this test, and three specimens were used for each test. The samples were allowed to cure as per Section 3.1, and cores were then extracted from the concrete cubes using a core drilling machine. The cored specimens were then covered with two epoxy coatings leaving only the top face exposed. Two coats of the epoxy coating were applied to ensure that the intended faces were waterproof. Since surface flaws could allow water to penetrate through the uncured coating, a heat gun was also used to eliminate bubbles in the epoxy.

For 35 days, the samples were submerged in a NaCl solution with a concentration of 165 ± 1 g NaCl per L of solution. After being taken out of the solution, the samples were divided into predetermined 5 mm intervals as per ASTM C1556-11a (Table 1) by saw cutting to a depth of 20 mm for the 0.45 w/b specimens, and 25 mm for the 0.8 w/b specimens from the exposed concrete face. The depths were selected as it was expected that there would not be extensive chloride penetration over the 35-day exposure period. The samples were then allowed to dry in an oven at 70ºC for 72 hours, after which they were pulverised and stored in plastic Ziplock bags until the titrations were done.

The comparison was based on the chloride penetration into the concrete, not the fibre cement boards. The powder specimens were analysed for chloride concentrations using the potentiometric method. Titrations were used to determine the concentration of chlorides in the samples and are shown in Figure 3-5. The calibration results, where samples of known chloride concentration were tested, can be found in Appendix 8.4.2.

Figure 3-5: Potentiometric titration test machine

The concentration of chlorides measured by the mass cement would serve as a proxy for the penetration depth. The concrete densities were determined during the concrete compression tests by dividing the cube's measured weights by the volume of the cube. The concrete density of the 0.45 w/b mix was 2435 kg/m^3, and the concrete density for the 0.8 w/b concrete was 2387 kg/m^3 as per the mix design. Equation (1), which is the equation used to calculate the percentage of chlorides by mass cement, was used to determine the chloride penetrations according to the concrete and the cement mass.

$$\%Cl_{cement} = (((m_{CL} \,.\, M_T \,.\, V_T) / M_S) / 10) \,.\, (D_C / C_C) \tag{1}$$

Where:

M_S - Mass of the test sample (g)

M_T - Molarity of titrant (m/l)

m_{CL} - Molar mass of Chloride (g/mol)

D_C - Density of Concrete mix (kg/m^3)

C_C - Cement Content as per mix (kg/m^3)

V_T - Volume of titrant consumed during titration (ml)

$\%Cl_{concrete}$ - Percentage Chlorides by mass of concrete (%)

$\%Cl_{cement}$ - Percentage Chlorides by mass of cement (%)

Due to the cutting operation, the depths at which the chloride contents were measured were done in 5 mm intervals. Therefore, the average between the interval's top and bottom was regarded as the mean depth. The fact that the saw blade removed 3 mm when it was cut presented a challenge because the mean depth was not an accurate representation of the average depth, but can instead be used to represent the interval depth.

4. Results and discussion

This section presents and discusses the findings from the numerous tests which were carried out.

4.1 Interface shear bond test

4.1.1 Results

The average shear bond strengths, and the corresponding standard deviations are displayed in a bar graph in Figure 4-1 as the test findings (the detailed results can be found in Appendix 8.2). All specimens failed at the bond interface except for one specimen in the 0.8 w/b sample that failed prematurely due to delamination of the fibre cement board from the concrete. The delaminating sample was excluded from the analysis since it had already begun to de-bond before loading.

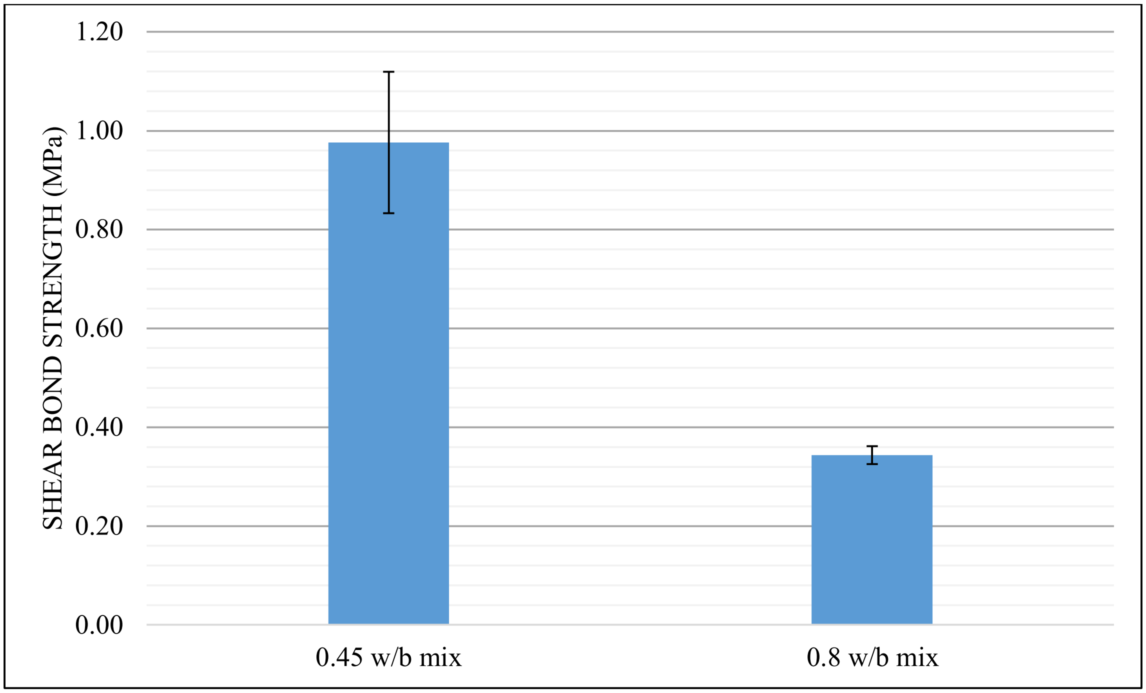


Figure 4-1: Bar Graphs showing the Shear Bond Strengths of the concrete mixes

The 0.8 w/b mix's average shear bond strength was 0.34 MPa compared to 0.98 MPa for the 0.45 w/b. The shear bond performance of the 0.45 w/b mix was nearly three times better than that of the 0.8 w/b mix. In contrast to the 0.8 w/b mix, which had a narrower distribution, the 0.45 w/b mix had a broader range of strengths. The 0.45 w/b had a standard deviation of 0.14, while the 0.8 w/b mix had a standard deviation of 0.02. These standard deviations represent the distribution of the data. The material strengths may account for some of the variations in bond strengths since the 0.8 w/b mix was much weaker (22.2 MPa) than the 0.45 w/b mix (50.7 MPa).

4.1.2 Discussion

The results of the interface shear bond test indicate that a bond can be established between the fibre cement board and the concrete. With an average bond strength of 0.98 MPa, the 0.45 w/b mix's bond strength results were three times better than those of the 0.8 w/b mix.

There were differences in the shear bond strengths between the two mixes (0.98 MPa for the 0.45 w/b mix, and 0.34 MPa for the 0.8 w/b mix), but this could be attributed to the differences in compressive strengths (50.7 MPa for the 0.45 w/b mix, and 22.4 MPa for the 0.8 w/b mix), and the compaction parameters (vibration compaction for the 0.45 w/b mix, and hand compaction for the 0.8 w/b mix). The development of the bond strength, in concrete repairs, is affected by the two phases of concrete: the viscous and solid states. In the viscous state, the extent to which the fresh concrete can embed into the concrete is affected by the compaction and workability of the mix. The test parameters varied the compactions across the mixes. The 0.8 w/b mix used hand compaction, and had a slump of 35 mm whereas the 0.45 w/b mix used vibration compaction, and had a slump of 80 mm. The slumps were determined as per SANS 5862. Also, in the hardened state, the bond strength is affected by the strength of the cured materials which develops as the compressive strength develops.

A calculation was made to assess what the load per square meter of fibre cement board would exert on the structure, and to verify that the acquired strengths are sufficient to withstand the dead loads of the fibre cement boards. By dividing the 15 mm thickness by the material's density, which was 1500 kg/m^3, the weight per square meter of fibre cement board was calculated giving a result of 22.50 kg/m^2. Using the weights per square meter and multiplying it by gravity, which is 9.81 m/s^2, translated it to a stress of 2.21 x 10^{-4} MPa of dead weight which would be applied per square meter of fibre board. This stress is well within the lowest result of 0.3 MPa that was determined from the shear bond strength tests. However, the live loading conditions were not taken into consideration because the underlying concrete offers a better strength capacity in scenarios where live loads would be used including the usage of fittings and cladding.

In practice, it would be advisable to have the surface roughening be done by the fibre cement board manufacturer. The manufacturer can use stringent quality controls as part of the manufacturing process to ensure that the surface roughness consistently satisfies the requirements. Using a system that uses mechanical anchorage to bond the fibre cement board to the concrete is an alternate method of linking the fibre cement board to the concrete. These methods may be in the form of anchors that are cast into the boards at the time of production. When fibre cement boards are utilized as permanent formwork, the anchors are encased by the concrete during casting and become embedded in the concrete, connecting the concrete to the permanent formwork. If the mechanical anchors are composed of materials that are susceptible to degradation, they may deteriorate and result in a weakened bond. Hence, they should be inert. Additionally, if steel anchors are employed, the deteriorative products may cause concrete to deteriorate as well.

Differential strains that result from internal (shrinkage) and external (temperature differences and loading) factors result in the development of stresses at the bond interface, and was not investigated in this study. Understanding the properties of fibre cement boards is essential in order to comprehend the differential strain interactions at the bond interface. This is influenced by the characteristics of fibre cement boards, such as the thermal coefficient, absorptive capacity, and directional elastic moduli.

4.2 Durability index tests

The results of the durability index tests are presented in this section (the detailed results can be found in Appendix 8.3). The classification of the concrete's samples was done according to the durability index classification system as displayed in Table 3-4. Statistical analyses including mean, standard deviation, and t-test analysis were used to assess the data. A two tailed independent t-test was completed with a significance value of 0.05. The null hypothesis for the t test is that there is no statistically significant difference between the samples.

4.2.1 Results

4.2.1.1 Oxygen permeability index

The results of the oxygen permeability test are displayed in Figure 4-2. The test results show that the 0.45 w/b mix performed better than the 0.8 w/b mix throughout the parameters examined. The 0.8 w/b samples were classed as poor-quality concrete, while the 0.45 w/b samples were classed as good-quality concrete. When the averages and standard deviations were considered, there was no overlap between the results for the two mixes. The lowest OPI range value for the 0.45 w/b mix was 9.60, and the highest OPI range value for the 0.8 w/b mix was 9.47. The resulting t-test p-value was 8.08 x 10^{-6} indicating that there are significant differences between the two mixes' results. This confirms that the 0.45 w/b performed better than the 0.8 w/b mix.

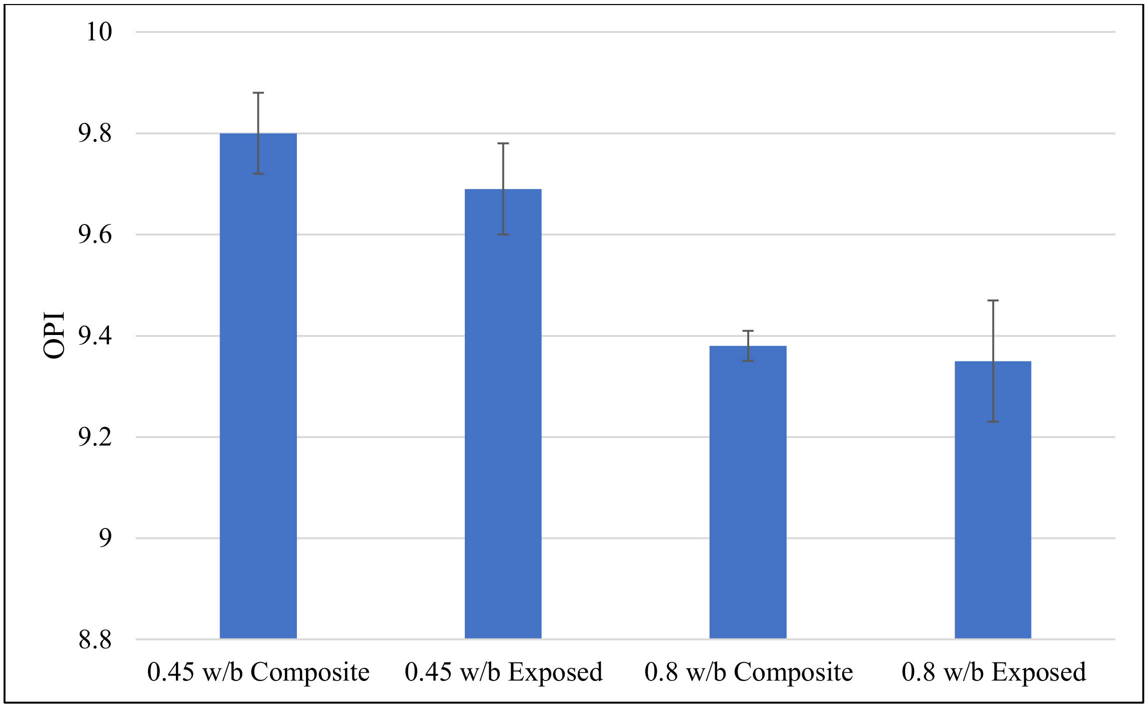


Figure 4-2: OPI results for tested samples

According to the results the average OPI for the composite 0.45 w/b sample was 9.80 compared to 9.69 for the exposed sample. The standard deviations of the composite and exposed sample indicate a definite overlap of data within the 0.45 w/b mix. The difference in results was negligible as the t-test p-value for the composite and exposed samples were 0.09 which is above the 0.05 significance value.

The average OPI for the composite 0.8 w/b sample was 9.38, whereas the average for the exposed sample was 9.35. According to the averages, the composite mix and exposed samples for the 0.8 w/b mix performed the same. The t-test p-value for the 0.8 w/b composite and exposed samples was 0.62, which is greater than the 0.05 significance level, indicating that the differences in results are negligible.

4.2.1.2 Water sorptivity test

The results of the water sorptivity test are displayed in Figure 4-3. The average sorptivity result for the 0.45 w/b exposed sample was taken over three specimens, not four, due to the mass in one of the specimens being inconsistent with the others rendering the specimen invalid.

The sorptivity data indicates that the 0.45 w/b mix outperformed the 0.8 w/b mix across all the parameters tested. According to the sorptivity results, the 0.8 w/b samples were categorised as poor-quality concrete, whereas the 0.45 w/b samples were categorised as good-quality concrete. The lowest sorptivity range value for the 0.45 w/b mix was 10.25 mm/h$^{0.5}$, and the highest sorptivity range value for the 0.8 w/b mix was 12.16 mm/h$^{0.5}$. A t-test was performed on the 0.45 and 0.8 w/b samples, and the p-value was 8.00 x 10^{-7}, which was below the significance level of 0.05. This demonstrates that there is a significant difference between the samples and supports the observation that the 0.45 w/b mix performed better than the 0.8 w/b mix.

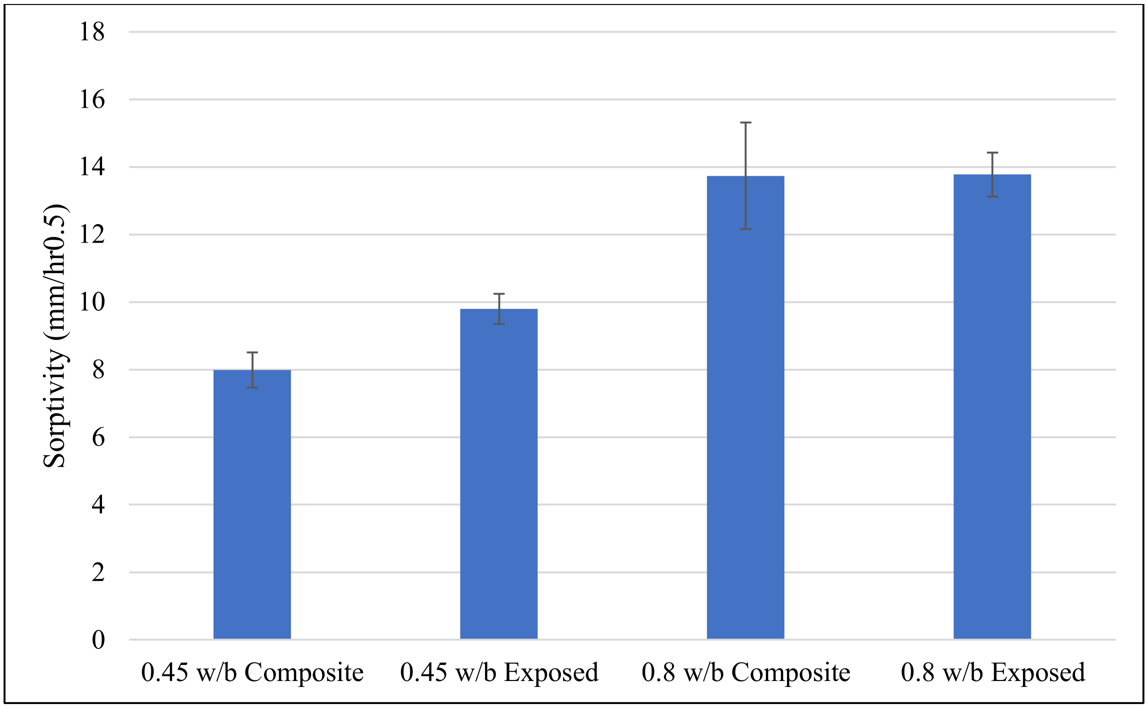


Figure 4-3: Sorbtivity results for tested samples

The composite 0.45 w/b sample had an average water sorptivity of 7.99 mm/h$^{0.5}$ as opposed to the exposed sample's 9.80 mm/h$^{0.5}$. The composite and exposed samples of 0.45 w/b mix had standard deviations of 0.52 and 0.45 respectively. The t-test for the sample resulted in a p-value of 5.16 x 10^{-3} which is below the significance value of 0.05. The t-test for the 0.45 w/b mix indicated that differences in results were significant, with the composite sample outperforming the exposed sample.

The composite 0.8 w/b sample had an average water sorptivity of 13.74 mm/h$^{0.5}$ as opposed to the exposed sample's 13.78mm/h$^{0.5}$. The standard deviations for the 0.8 w/b mix exposed and composite samples were 1.58 and 0.51 respectively. As opposed to the 0.45 w/b mix, the t-test for the 0.8 w/b mix indicated that the differences between the composite and exposed samples are negligible as the value was 0.97, which was notably higher than the significance value of 0.05.

4.2.1.3 Chloride conductivity test

The results of the chloride conductivity test are displayed in Figure 4-4. The conductivity data indicated that the 0.45 w/b mix outperformed the 0.8 w/b mix, with the 0.8 w/b samples categorized as a very poor-quality concrete, while the 0.45 w/b samples were categorized as a good-quality concrete. The difference was confirmed to be significant by the t-test p-value of 4.03 x 10-7 because the final t-value was below the significance threshold. The 0.45 w/b mixes performed better than the 0.8 w/b mix, according to the t-test.

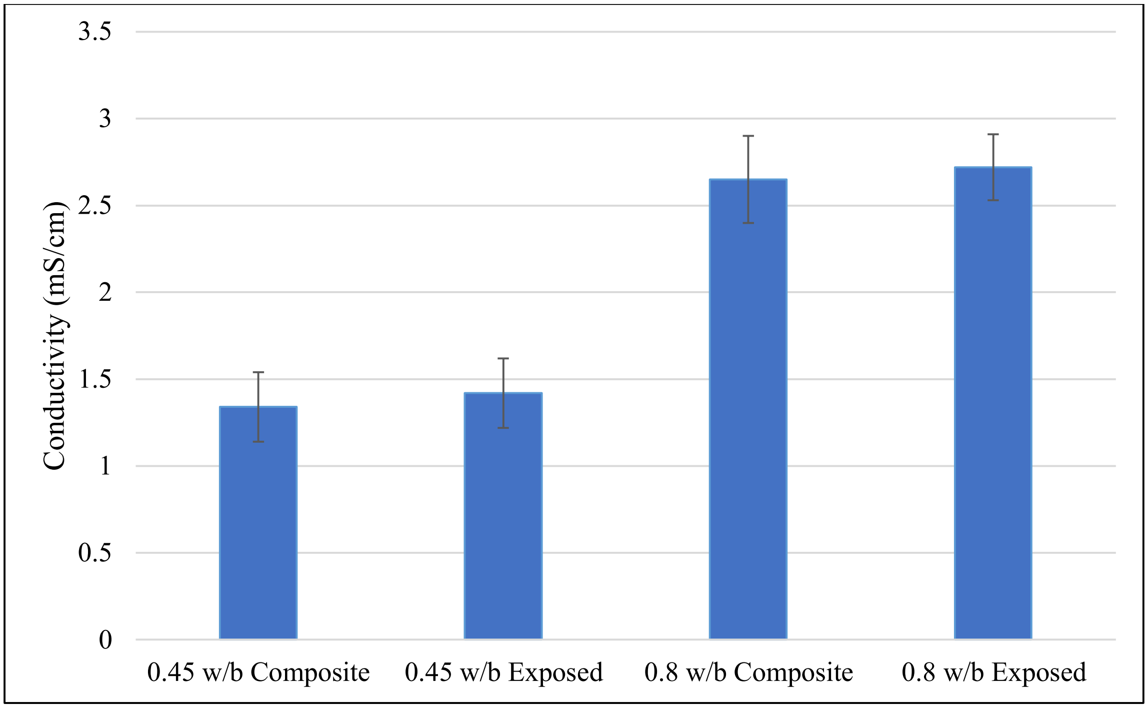


Figure 4-4: Conductivity results for tested samples

According to the results the average conductivity for the composite 0.45 w/b sample was 1.34 compared to 1.42 for the exposed sample. The standard deviations of the 0.45w/b composite and exposed samples were 0.2. The difference in results was negligible as the t-test p-value for the composite and exposed samples were 0.59 which is above the 0.05 significance value.

The average conductivity of the composite 0.8 w/b sample was 2.65 mS/cm as opposed to 2.72 mS/cm for the exposed sample. The standard deviations for the composite and exposed samples of the 0.8 w/b mix were 2.65 and 2.72, respectively. The t-test for the 0.8 w/b mix demonstrated that there were no significant differences between the composite and exposed samples because the p-value was 0.65, which was higher than the significance value of 0.05.

4.2.2 Discussion

According to the durability index test results, there was no advantage to using fibre cement board as a permanent formwork over being exposed.

Based on the test results and analysis, the 0.45 w/b mix outperformed the 0.8 w/b mix. The results for the 0.45 w/b mix across all the durability index tests indicated that the concrete was classed as good-quality concrete, whereas the 0.8 w/b mix the concrete was classified as either poor or very poor. The outcome can be attributed to the fact that the 0.45 w/b mix had better compaction (vibrator compacted) than the 0.8 w/b mix (hand compacted). The amount of voids in the concrete is influenced by the compaction effort. A higher void content is related to more permeable concrete because voids offer no resistance to the flow of ions within a concrete.

Comparing the composite samples to the exposed samples, fibre cement boards did not offer any additional curing benefits. While there was no improvement, there was also no decrease in the curing effectiveness. Due to the unfavourable evaporation conditions, it's possible that the samples' placement in the controlled environment did not result in significant amounts of water being drawn from the exposed concrete.

As the development of the concrete's microstructure is correlated with curing, it impacts how easily harmful substances can penetrate the concrete. The better the concrete is cured, the denser the micro-structure becomes which inhibits the penetrations of harmful ions through all the concrete’s transport mechanisms. To prevent water from evaporating from the surface of concrete, a variety of methods are applied in practice, such as coatings, plastic wraps, and maintaining a wet environment for the concrete.

Future research could examine the durability characteristics of the fibre cement boards. The challenge in determining the durability index parameters of the fibre cement boards arises because the thicknesses are limited to a maximum of 15 mm. If boards of sufficient thickness can be obtained to perform the durability index tests on, a better understanding of the boards, and the durability properties they provide to the underlain concrete can be gained.

4.3 Bulk diffusion test

This section presents the findings of the bulk diffusion testing. The detailed chloride concentrations for both mixes are presented in Appendix 8.4.1. The bulk diffusion test on all samples revealed a decrease in the quantity of chlorides in the concrete at different depths as shown in Figure 4-5 and Figure 4-6 respectively. The chloride threshold value of 0.4% chloride content by mass cement is shown in Figure 4-5 and Figure 4-6. If the reinforcing steel is located at that depth, this is the point above which corrosion initiation will occur.

The exposed samples of the 0.8 w/b mix design had an average of 6.4% chloride by mass of cement at the surface level. In contrast, the covered samples had 3.6% chlorides by mass of cement at the surface level where the chloride concentrations were expected to be highest. The exposed samples of the 0.45 w/b mix design had an average of 8.0% chloride by mass of cement at the surface level. In contrast, the covered samples had 2.1% chlorides by mass of cement at the surface level where the chloride concentrations were expected to be highest.

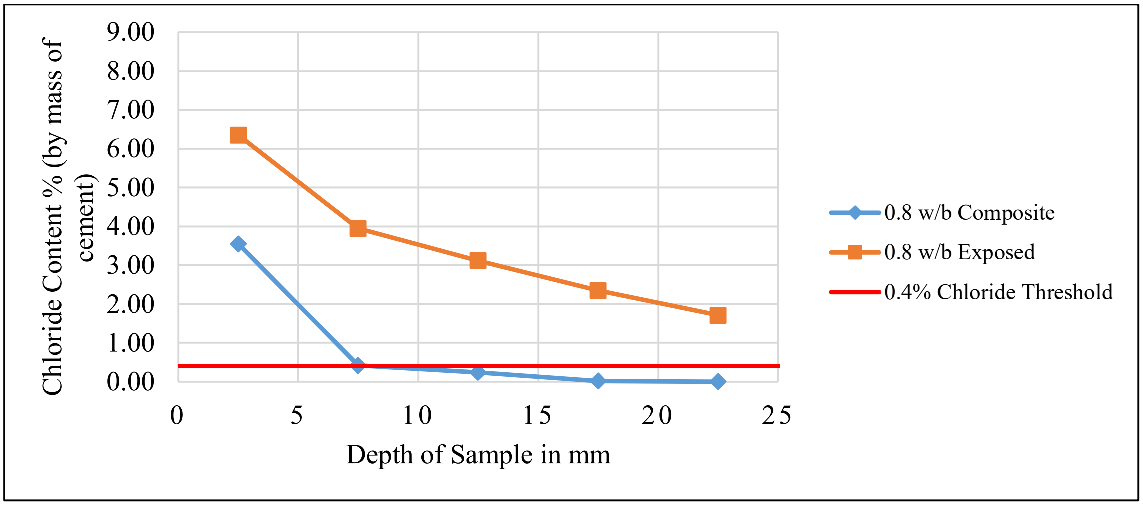


Figure 4-5: 0.8 w/b concrete's chloride concentrations at various depths

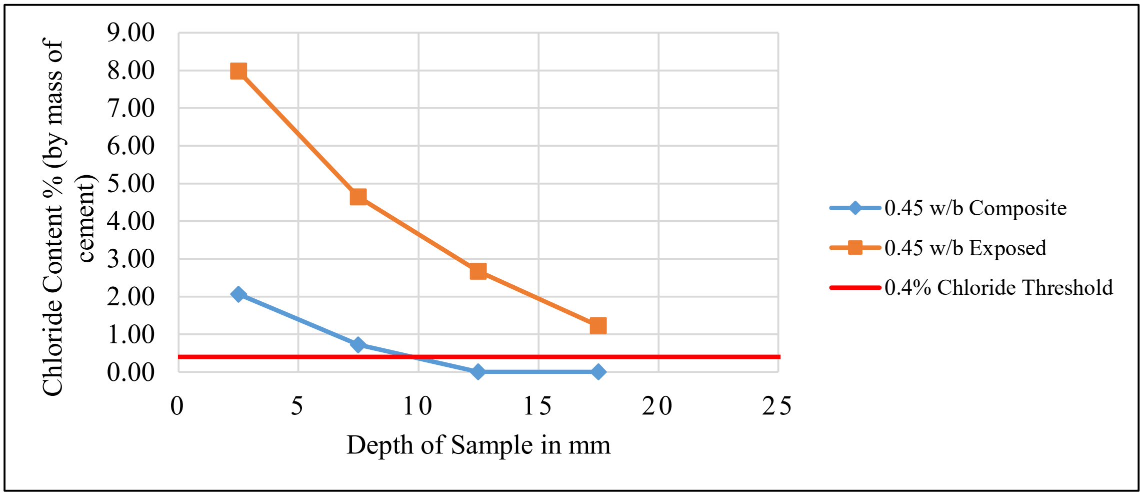


Figure 4-6: 0.45 w/b concrete's chloride concentrations at various depths

According to the findings, there was a general decrease in chlorides in all of the samples of the composite compared to exposed concrete at all depths. Over the first two depth increments, the rate of decrease of chlorides in the composite 0.8 w/b samples were faster than the exposed sample. The chloride concentration in the 0.8 w/b composite specimen declines rapidly and proceeds to flatten out once it approaches the chloride threshold value, whereas in the exposed specimen it remains well above the chloride threshold value even as the chloride concentration decreases. The rate of decrease for the exposed sample increases above that of the composite sample from depths increments two to five. The minimum chlorides in the 0.8 w/b exposed sample are at the fifth depth increment (22.5 mm average depth level) at 1.7% chloride by mass cement, whereas the 0.8 w/b composite sample had reached 0.0% at the fourth depth increment (17.5 mm average depth level). The composite sample's chloride concentration drops below the chloride threshold value at 8.0 mm whereas the exposed sample does not drop below the threshold value. As in the case of the 0.8 w/b mix, the 0.45 w/b composite samples had lower chloride concentrations than the 0.45 w/b exposed samples at all depth increments. The 0.45 w/b composite specimen's chloride concentration steadily decreases until it achieves 0.0% chlorides by mass cement, while the exposed specimen's chloride concentration remains above the chloride threshold value. The composite sample's chloride concentration drops below the chloride threshold value at 8.7 mm whereas the exposed sample does not drop below the threshold value. The minimum chloride level at the fourth depth increment (17.5 mm average depth level) of the 0.45 w/b exposed sample was 1.2% chloride by mass cement, whereas the composite samples reached 0.0% at the third depth increment (12.5 mm average depth level).

The chloride percentage by mass of cement within the first two intervals was higher for the 0.45 w/b mix as compared to the 0.8 mix. As shown in equation (1), the chloride % by mass cement should be lower because the 0.45 w/b mix contained more cement than the 0.8 w/b mix. However, the cement content of the mixes also influences chlorides binding, the 0.45 w/b mix would therefore bind more chlorides than the 0.8 w/b mix. In addition, this could be further exacerbated by the skin effect. The skin effect, a phenomenon in which the surface of a concrete has more cement paste than the interior. According to (Andrade, 2007), the composition of the concrete at the surface is different from that of the interior mass. Compared to the interior of the concrete, which contains more stone, the concrete surface has a higher cement content at the surface. The skin effect would affect both mixes but would be more pronounced in the 0.45 w/b mix as it has a higher cement content than the 0.8 w/b mix.

In

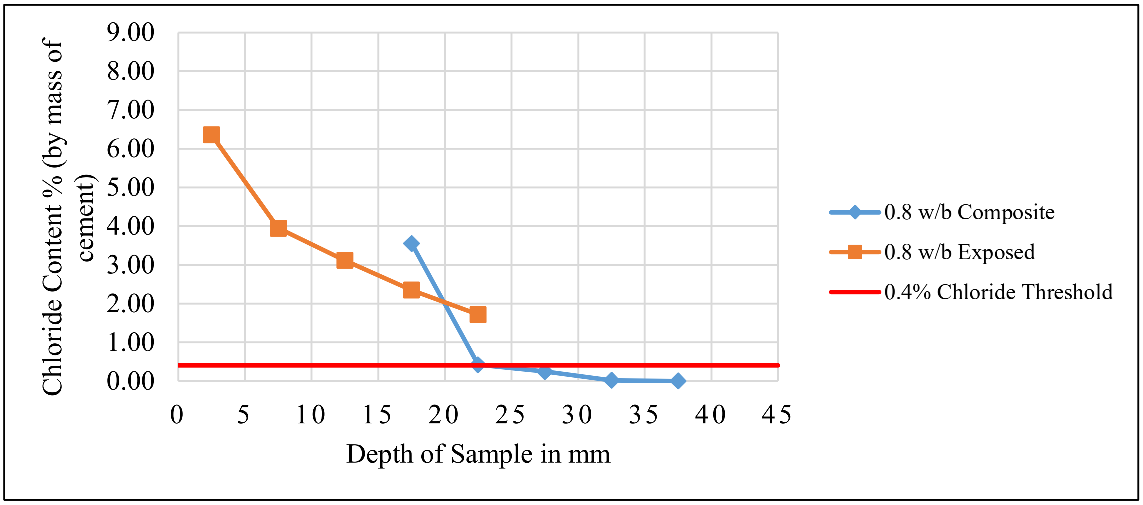


Figure 4-7 and Figure 4-8, the fibre cement boards were taken into account as serving as a concrete cover. The chloride content % curves of the composite samples' curves were shifted by the 15 mm thickness of the fibre cement boards . In

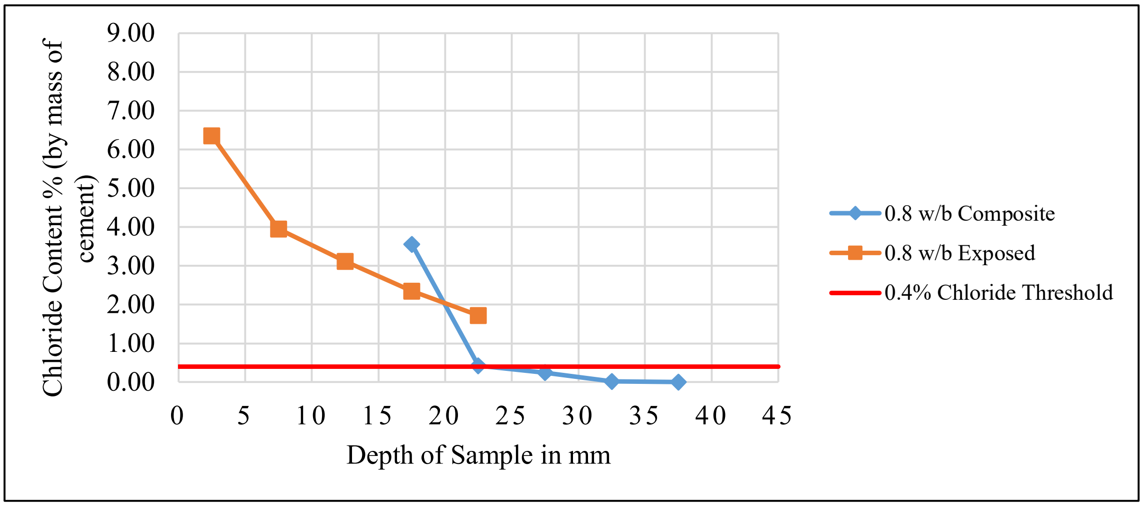


Figure 4-7, the composite sample had 1.2% more chlorides by mass cement than the exposed sample at the 17.5 mm average interval depth. The composite sample's rate of chloride reduction is significantly higher than the exposed sample's over the 17.5-22.5 mm average interval depth. The 0.45 w/b composite sample in Figure 4-8 had 0.8% more chlorides by mass cement than the exposed sample at the 17.5 mm average interval depth.

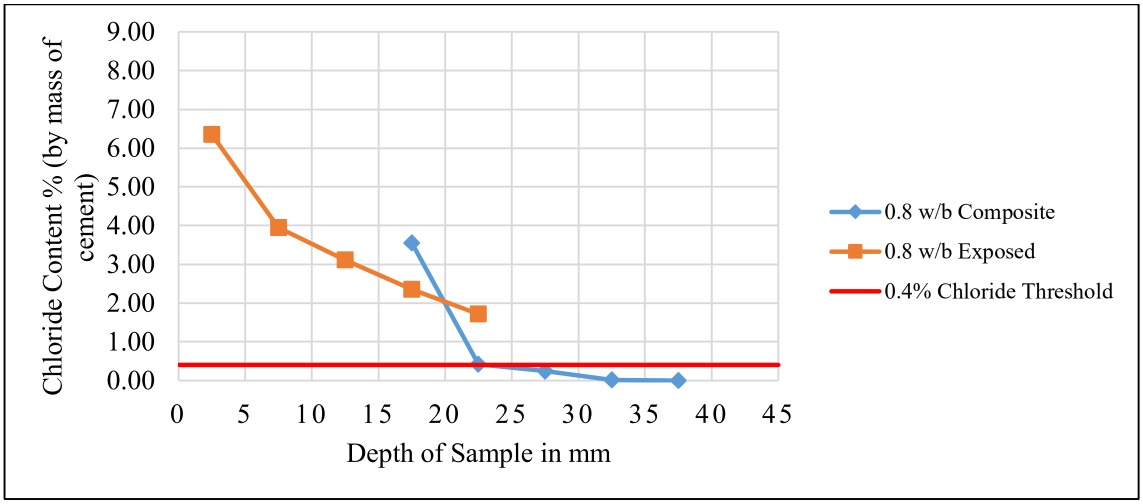


Figure 4-7: 0.8 w/b chloride concentration when accounting for the depth of the fibre cement board

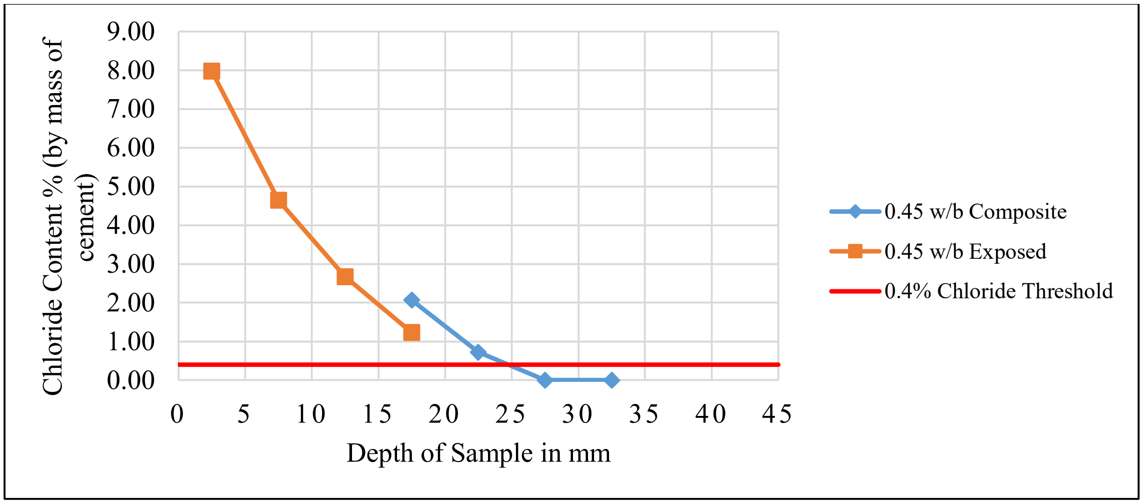


Figure 4-8: 0.45 w/b chloride concentration when accounting for the depth of the fibre cement board

In the 0.45 w/b mix the composite sample's rate of chloride reduction was comparable to that of the exposed sample. It can thus be posited that the fibre cement boards serve as a good-quality concrete cover that is placed over the concrete. While the performance of the fibre cement board compared similarly to that of the concrete in the 0.45 w/b, it performed significantly better than the 0.8 w/b concrete.

4.3.1 Discussion

An important benefit to fibre cement boards use as a permanent formwork was displayed as the composite samples provided additional protection to the penetration of the chlorides across both concrete mixes as compared to the exposed samples. The performance of the fibre cement board was superior to that of the 0.8 w/b concrete and comparable to that of the 0.45 w/b concrete when the permanent formwork was accounted for as a functioning cover.

The fibre cement board provided protection to the underlying concrete from the ingress of chlorides. The protective qualities provide durability benefits as the depth that chlorides must penetrate to reach the steel is increased when using the fibre cement board. Permanent formworks are allowed under SANS 10-100-2 because they reduce the concrete's direct contact with the external environment which lowers the required concrete cover depth.

SANS 10-100-2 only specifies that the material qualities of permanent formworks must not be impacted by corrosion and weathering. When using permanent formwork, a decrease in cover is permitted, but because the required permanent formwork materials are not specified, the reduction is conservative. The permanent formwork cannot take the place of the cover, as required by the code, and a minimum cover must be provided.

The bulk diffusion test results have shown that the fibre cement boards performed similarly to a concrete of good quality and thus can be accounted for as functioning concrete cover. For poor quality concrete, replacing the cover would be even more advantageous because the permanent formwork would offer greater durability than the concrete. Additionally, because fibre cement board weighs less than concrete, it will contribute less to the structure's weight than concrete would. Savings could result from lowering the cover requirements because less concrete would be required to construct the structure. The similar performance of the fibre cement board to the 0.45 w/b mix was not expected. It was assumed that fibre cement board would perform similarly to a low-quality concrete as was discovered by Moser (2019) in his experiments using the durability index test methods.

The effectiveness of the fibre cement board to protect against mechanisms of deterioration such as carbonation, acid attack, and attack by softwaters was not examined in the study. While the results suggest that fibre cement boards can offer some protection against chloride penetration, this assumption should not be made for other types of deterioration until further research is done.

5. Conclusion

Due to the historical use of temporary formwork and its capacity to be re-used, the construction industry has not widely adopted permanent formwork. Since installing and removing the forms is the system's main cost component, the reusability of temporary forms presents unique issues.

This study attempted to determine whether permanent formwork, an alternative to temporary formwork, could offer extra advantages not discovered in the existing literature. The research examined the underlying concrete's durability using the durability index tests, which included tests for oxygen permeability, water sorptivity, and chloride conductivity. The bulk diffusion test was used to determine if the underlying concrete is protected from chloride exposure when fibre cement board is used as permanent formwork. Finally, the shear bond performance of fibre cement boards to the concrete was studied using an interface shear bond test to establish whether the fibre cement board can function as permanent formwork.

The interface shear bond test findings demonstrate that a bond can be created between the cast concrete and fibre cement boards. This is given that surface preparation is performed on the fibre cement board prior to concrete casting. If used as a permanent formwork, the bond has been proven to have enough strength to support the dead weight of the boards. However, whether the bond strength is sufficient to withstand stresses from external factors such as differential strains between the boards and concrete needs to be further investigated. In cases where fibre cement boards are utilised, robust quality controls should be implemented because the surface preparation process depends on good workmanship. The risk of de-bonding considerably increases if tight quality controls are not maintained.

Craftsmanship is essential for establishing the bond between the concrete and the fibre cement board. On the construction site, it is likely that proper work practices will not be followed. Boards that are affected by this might not bond correctly or at all. These situations enhance the chance of delamination, which raises the danger of injury from boards de-bonding and falling.

The investigation's findings indicate that using fibre cement board as a permanent formwork has no beneficial effects on the concrete's durability. However, there were also no adverse effects on the concrete’s durability performance when the fibre cement boards were used. The study focused on the curing effectiveness the fibre cement board provided to the underlaying concrete but did not take into consideration the durability properties of the fibre cement board.

According to the bulk diffusion test results, the fibre cement boards successfully decreased the proportion of chlorides in the concrete over the different interval depths and performed comparably to a good quality concrete. Therefore, it follows that fibre cement boards offer additional protective features beyond those of concrete. According to the results of the bulk diffusion tests conducted for this study, the fibre cement board had protective qualities in withstanding chloride penetration that were superior to those of poor-quality concrete, and are on par with good-quality concrete. In scenarios in which fibre cement boards are used on structures with poor quality concrete, for the equivalent cover specification of fibre cement board would result in more durable structures that are better suited to withstand their external environments.

6. Recommendations

This study has investigated the use of fibre cement boards as permanent formwork. From this study, further areas have been identified for future research.

The study's scope was constrained to a short-duration laboratory investigation. Future studies could extend the study's duration and use comparable approaches to evaluate the permanent formwork's performance in situ.

Research could be conducted on the differential in strains caused by internal (shrinkage) and external (temperature variations and loading) factors that affect the bond interface. The thermal coefficient, wet/dry deformation characteristics, and stiffness characteristics of fibre cement board could also be the subject of research.

The durability of the fibre cement boards may be able to be ascertained through additional research. This research requires the use of boards that correspond to the requirements for the durability index test sample thicknesses.

It was investigated how fibre cement board provides protection against the entry of chlorides, but there are other types of deterioration from which the concrete may also be protected by fibre cement board. Other mechanisms of deterioration such as carbonation and chemical attack (acid and softwater) can be used to further study the protective capabilities of fibre cement board in permanent formwork applications.

7. References

ACI (American Concrete Institute), 2002. ACI 544.1 R-96: *Report on Fiber Reinforced Concrete*. Farmington Hills, MI, USA: American Concrete Institute.

Addis, B. & Goodman, J. 2009. Concrete mix design. In. *Fulton's concrete technology. G. Owens,* 9th ed. Midrand, South Africa: Cement & Concrete Institute. 219-228.

Alexander, M.G., Ballim, Y. & Mackechnie, J.R. 2017. *Durability Index Testing Procedure Manual.* Cape Town: University of Cape Town & University of Witswatersrand Johannesburg.

Alexander, M. G., Mackechnie, J. R., & Ballim, Y. (1999). Guide to the use of durability indexes for achieving durability in concrete structures. *Research monograph, 2*. University of Cape Town, South Africa.

Alexander, M. & Beushausen, H. 2009. Concrete repair. In. *Fulton's concrete technology. G. Owens,* 9th ed. Midrand, South Africa: Cement & Concrete Institute. 393-412.

Andrade, C. 2007. Corrosion of steel reinforcement. *WIT Transactions on State of the Art in Science and Engineering.*28:187-215. DOI:10.2495/978-1-84564-032-3/06.

Ballim, Y., Alexander, M. & Beushausen, H. 2009. Durability of concrete. In *Fulton's concrete technology. G. Owens,* 9th ed. Midrand, South Africa: Cement & Concrete Institute. 155-188

Bank, L.C., Malla, A.P., Oliva, M.G., Russell, J.S., Bentur, A. & Shapira, A. 2009. A model specification for fiber reinforced non-participating permanent formwork panels for concrete bridge deck construction. *Construction and Building Materials.*23(7):2664-2677.

Beushausen, H. & Alexander, M. 2008. Bond strength development between concretes of different ages. *Magazine of Concrete Research.* 1(60):65-74.

Beushausen, H. 2005. *Long-term performance of bonded concrete overlays subjected to differential shrinkage.* PhD thesis*,* University of Cape Town, South Africa.

Bissonnette, B., Vaysburd, A. & von Fay, K. 2012. Best Practices for Preparing Concrete Surfaces Prior to Repairs and Overlays. Denver: U.S. Department of the Interior.

Cement & Concrete Institute (South Africa). 2013. *Fundamentals of concrete.* 3rd ed. Midrand, South Africa: Cement and Concrete Institute

Claisse, P.A. Transport Properties of Concrete. *Concrete International.*27(1):43-48.

Courard, L., Bissonnette, B., Garbacz, A., Vaysburd, A. & Fay, K. 2018. Guidelines for concrete surface preparation: 10 years research and experience. *MATEC Web of Conferences.* 199:08004. DOI:10.1051/matecconf/201819908004.

Gohnert, M. 2000. Proposed theory to determine the horizontal shear between composite precast and in situ concrete. *Cement and Concrete Composites.* 22(6):469-476.

Gowripalan, N., Cabrera, J.G., Cusens, A.R. & Wainwright, P.J. 1990. Effect of curing on durability. *Concrete International.* 12:47-54.

Hanna, A. 1998. *Concrete Formwork Systems.* New York: Marcel Dekker.

Kellerman, J. 2009. Manufacture and handling of concrete. In. *Fulton's concrete technology. G. Owens,* 9th ed. Midrand, South Africa: Cement & Concrete Institute. 229-250.

Kepler, J.L., Darwin, D. & Locke Jr, C.E. 2000. *Evaluation of corrosion protection methods for reinforced concrete highway structures.* University of Kansas Center for Research, Inc.

Kumar, S. & Gupta, R.C, Blessen, S.T, Mehra,P. 2015. *Resistance to acid attack of cement concrete containing discarded tire rubber.* Punjab, India.UKIERI Concrete Congress – Concrete Research Driving Profit and Sustainability.

Mahima, S., Moorthi, P.V.P., Bahurudeen, A. & Gopinath, A. 2018. Influence of chloride threshold value in service life prediction of reinforced concrete structures. Sādhanā.

Malla, A., Bank, L., Shapira, A., Bentur, A., Russell, J., Oliva, M. & Khandekar, T. 2007. *Specification and Design of Fiber Reinforced Bridge Deck Forms for Use on Wide Flange T-Girders.* Springfield. Wisconsin Highway Research Program.

Middel, C. 2009. Formwork. In. *Fulton's concrete technology. G. Owens,* 9th ed. Midrand, South Africa: Cement & Concrete Institute. 251-264.

Moser, R. 2019. *Fibre cement panels as permanent formwork for reinforced concrete elements.* Undergraduate Thesis. University of Cape Town.

Oberholster, B. 2009. Alkali-silica reaction. In. *Fulton's concrete technology. G. Owens,* 9th ed. Midrand, South Africa: Cement & Concrete Institute

Otieno, M., Alexander, M. & Beushausen, H. 2010. *Transport Mechanisms in Concrete.* Cape Town: Concrete Materials and Structural Intergrity Research Group.

Owens, G. 2009. *Fulton's concrete technology.* Midrand: Cement & Concrete Institute.

Perrie, B. 2009. Strength of hardened concrete. In. *Fulton's concrete technology. G. Owens,* 9th ed. Midrand, South Africa: Cement & Concrete Institute. 97-110.

Peurifoy, R. L., Oberlender, G D. 2011. *Formwork for concrete structures.* New York: McGraw-Hill.

Qu, F., Li, W., Dong, W., Tam, V.W.Y. & Yu, T. 2021. Durability deterioration of concrete under marine environment from material to structure: A critical review. *Journal of Building Engineering.* 35:102074

Rajabipour, F., Giannini, E., Dunant, C., Ideker, J.H. & Thomas, M.D.A. 2015. Alkali–silica reaction: Current understanding of the reaction mechanisms and the knowledge gaps. *Cement and Concrete Research.* 76:130-146.

SANS (South African National Standard). 2014. SANS 10100:2. 2014. *The Structural Use of Concrete. Part 2: Materials and execution of work.* Pretoria: South African Bureau of Standards Division.

Santos, D., Santos, P. & Dias-da-Costa, D. 2012. Effect of surface preparation and bonding agent on the concrete-to-concrete interface strength. *Construction and Building Materials.* 37:102–110.

Silfwerbrand, J. 1990. Improving concrete bond in repaired bridge decks. *Concrete International*. 12:61-66.

Talotti, M. 2014. *Influence of substrate moisture preparation on concrete overlay bond strength.* MSc Thesis Cape Town. University of Cape Town.

Wrigley, R.G. 2001. *Permanent formwork in construction.* United Kingdom: Construction Industry Research & Information Association (Ciria).

8. Appendixes

8.1 Compressive strength results

Sample No.	Specified Strength (MPa)	Date Cast	Age of Test (days)	Date Tested	Slump* (mm)	Compaction Type	Dimension (mm) (1)	Dimension (mm) (2)	Dimension (mm) (3)	Mass (kg)	Gauge Reading (kN)	Density (kg/m^3)	Compressive Strength (MPa)	Mean Strength (MPa)
0.45 Cube 1 (7 days)	40	09-09-2022	7	16-09-2022	80	Vibration Compaction	100.36	100.28	100.75	2.465	38.20	2431	38.0	39.9
0.45 Cube 2 (7 days)	40	09-09-2022	7	16-09-2022			100.22	100.04	100.81	2.435	41.00	2409	40.9	
0.45 Cube 3 (7 days)	40	09-09-2022	7	16-09-2022			100.30	100.11	100.79	2.450	41.00	2421	40.8	
0.8 Cube 1 (7 days)	18	10-09-2022	7	17-09-2022	35	Hand Compaction	100.31	100.08	101.20	2.440	18.20	2402	18.1	18.4
0.8 Cube 2 (7 days)	18	10-09-2022	7	17-09-2022			100.25	100.88	100.27	2.455	19.20	2421	19.0	
0.8 Cube 3 (7 days)	18	10-09-2022	7	17-09-2022			100.14	100.04	100.43	2.415	18.20	2400	18.2	
0.45 Cube 1 (28 days)	40	09-09-2022	28	07-10-2022	80	Vibration Compaction	100.10	100.83	100.24	2.450	50.20	2422	49.7	50.7
0.45 Cube 2 (28 days)	40	09-09-2022	28	07-10-2022			99.87	100.64	100.70	2.420	51.80	2391	51.5	
0.45 Cube 3 (28 days)	40	09-09-2022	28	07-10-2022			99.61	100.51	100.65	2.430	50.80	2411	50.7	
0.8 Cube 1 (28 days)	18	10-09-2022	28	08-10-2022	35	Hand Compaction	101.81	100.20	99.95	2.390	24.20	2344	23.7	22.4
0.8 Cube 2 (28 days)	18	10-09-2022	28	08-10-2022			100.92	99.94	100.97	2.375	21.90	2332	21.7	
0.8 Cube 3 (28 days)	18	10-09-2022	28	08-10-2022			100.77	99.74	99.93	2.395	21.80	2385	21.7	

8.2 Bond strength Test Results

Sample	Mean Compressive Strength at 28 days (MPa)	Slump (mm)	Compaction Type	Shear Bond Strength (MPa)	Failure Plane
0.45 w/b Cube 1	50.7	80	Vibration Compaction	1.1	Bond Interface
0.45 w/b Cube 2				1.1	Bond Interface
0.45 w/b Cube 3				0.8	Bond Interface
0.45 w/b Cube 4				0.9	Bond Interface
0.8 w/b Cube 1	22.4	35	Hand Compaction	0.4	Bond Interface
0.8 w/b Cube 2				0.3	Bond Interface
0.8 w/b Cube 3				0.4	Bond Interface
0.8 w/b Cube 4				0.0	Delamination of Overlay

8.3 Durability index results

8.3.1 Oxygen permeability results

Summary of 0.8 w/b Exposed OPI test results

Disk Number	k (m/s)	OPI
1	4.02E-10	9.40
2	3.22E-10	9.49
3	5.60E-10	9.25
4	5.54E-10	9.26
Mean	**4.60E-10**	**9.35**
S.D.	1.17E-10	0.12
COV (%)	25	1.24

Summary of 0.8 w/b Composite OPI test results

Disk Number	k (m/s)	OPI
1	4.06E-10	9.39
2	3.77E-10	9.42
3	4.26E-10	9.37
4	4.51E-10	9.35
Mean	**4.15E-10**	**9.38**
S.D.	3.13E-11	0.03
COV (%)	8	0.35

Summary of 0.45 w/b Exposed OPI test results

Disk Number	k (m/s)	OPI
1	1.57E-10	9.80
2	2.37E-10	9.63
3	1.99E-10	9.70
4	2.38E-10	9.62
Mean	**2.08E-10**	**9.69**
S.D.	3.86E-11	0.09
COV (%)	19	0.88

Summary of 0.45 w/b Composite OPI test results

Disk Number	k (m/s)	OPI
1	1.55E-10	9.81
2	1.91E-10	9.72
3	1.70E-10	9.77
4	1.22E-10	9.91
Mean	**1.59E-10**	**9.80**
S.D.	2.90E-11	0.08
COV (%)	18	0.84

8.3.2 Sorptivity test results

Summary of 0.8 w/b exposed water sorptivity and porosity test results

Disk Number	Sorptivity (mm/hr$^{0.5}$)	Porosity (%)
1	14.26	12.72
2	13.32	11.20
3	13.11	11.95
4	14.41	11.67
Mean	**13.78**	**11.89**
S.D.	0.65	0.63
COV (%)	4.75	5.34

Summary of 0.8 w/b composite water sorptivity and porosity test results

Disk Number	Sorptivity (mm/hr$^{0.5}$)	Porosity (%)
1	13.57	11.40
2	12.65	11.95
3	12.72	11.27
4	16.18	12.50
Mean	**13.74**	**11.78**
S.D.	1.58	0.55
COV (%)	11.5	4.71

Summary of 0.45 w/b exposed water sorptivity and porosity test results

Disk Number	Sorptivity (mm/hr$^{0.5}$)	Porosity (%)
1	10.20	11.83
2	9.90	11.92
3	Invalid	Invalid
4	9.30	10.86
Mean	**9.80**	**11.54**
S.D.	0.45	0.59
COV (%)	4.64	5.11

Summary of 0.45 w/b composite water sorptivity and porosity test results

Disk Number	Sorptivity (mm/hr$^{0.5}$)	Porosity (%)
1	7.26	10.99
2	8.01	10.21
3	8.25	10.13
4	8.44	9.87
Mean	**7.99**	**10.30**
S.D.	0.52	0.48
COV (%)	6.46	4.71

8.3.3 Chloride conductivity test results

Summary of 0.8 w/b Exposed chloride conductivity test results

Disk Number	Conductivity (mS/cm)	Porosity (%)
1	2.48	5.51
2	2.76	4.73
3	2.95	5.52
4	2.7	5.29
Mean	**2.72**	**5.27**
S.D.	0.19	0.19
COV (%)	7.09	7.02

Summary of 0.8 w/b Composite chloride conductivity test results

Disk Number	Conductivity (mS/cm)	Porosity (%)
1	2.72	5.10
2	2.87	5.12
3	2.29	4.83
4	2.71	4.74
Mean	**2.65**	**4.95**
S.D.	0.25	0.25
COV (%)	9.44	3.85

Summary of 0.45 w/b Exposed chloride conductivity test results

Disk Number	**Conductivity (mS/cm)**	**Porosity (%)**
1	1.40	4.35
2	1.71	4.64
3	1.31	4.66
4	1.27	4.35
Mean	**1.42**	**4.50**
S.D.	0.20	0.20
COV (%)	14.01	3.90

Summary of 0.45 w/b Composite chloride conductivity test results

Disk Number	**Conductivity (mS/cm)**	**Porosity (%)**
1	1.04	4.38
2	1.51	4.30
3	1.43	4.78
4	1.39	4.33
Mean	**1.34**	**4.45**
S.D.	0.20	0.20
COV (%)	15.23	5.04

8.4 Bulk diffusion test

8.4.1 Test results

0.8 water/binder ratio fibre cement covered chloride penetrations results

Sample	Depth (mm)	Average depth (mm)	Chloride Content % (by mass of concrete)	Chloride Content % (by mass of cement)
1	0-5	2.5	0.360	3.61
	5-10	7.5	0.036	0.36
	10-15	12.5	0.024	0.24
	15-20	17.5	0.000	0.00
	20-25	22.5	0.000	0.00
2	0-5	2.5	0.354	3.56
	5-10	7.5	0.035	0.36
	10-15	12.5	0.025	0.26
	15-20	17.5	0.005	0.05
	20-25	22.5	0.000	0.00
3	0-5	2.5	0.360	3.48
	5-10	7.5	0.036	0.54
	10-15	12.5	0.024	0.23
	15-20	17.5	0.000	0.00
	20-25	22.5	0.000	0.00

0.8 water/binder ratio exposed concrete chloride penetrations results

Sample	Depth (mm)	Average depth (mm)	Chloride Content % (by mass of concrete)	Chloride Content % (by mass of cement)
1	0-5	2.5	0.620	6.23
	5-10	7.5	0.401	4.03
	10-15	12.5	0.383	3.84
	15-20	17.5	0.255	2.56
	20-25	22.5	0.170	1.71
2	0-5	2.5	0.628	6.31
	5-10	7.5	0.316	3.17
	10-15	12.5	0.280	2.82
	15-20	17.5	0.182	1.83
	20-25	22.5	0.158	1.59
3	0-5	2.5	0.649	6.53
	5-10	7.5	0.461	4.64
	10-15	12.5	0.267	2.69
	15-20	17.5	0.265	2.66
	20-25	22.5	0.184	1.85

0.45 water/binder ratio fibre cement exposed chloride penetrations results

Sample	**Depth (mm)**	**Average depth (mm)**	**Chloride Content % (by mass of concrete)**	**Chloride Content % (by mass of cement)**
1	0-5	2.5	0.826	2.11
	5-10	7.5	0.402	0.68
	10-15	12.5	0.244	0.00
	15-20	17.5	0.117	0.00
2	0-5	2.5	0.825	2.18
	5-10	7.5	0.447	0.82
	10-15	12.5	0.329	0.00
	15-20	17.5	0.108	0.00
3	0-5	2.5	0.731	1.90
	5-10	7.5	0.538	0.66
	10-15	12.5	0.224	0.00
	15-20	17.5	0.142	0.00

0.45 water/binder ratio fibre cement covered chloride penetrations results

Sample	**Depth (mm)**	**Average depth (mm)**	**Chloride Content % (by mass of concrete)**	**Chloride Content % (by mass of cement)**
1	0-5	2.5	0.210	8.30
	5-10	7.5	0.068	4.04
	10-15	12.5	0.000	2.45
	15-20	17.5	0.000	1.17
2	0-5	2.5	0.217	8.29
	5-10	7.5	0.082	4.49
	10-15	12.5	0.000	3.30
	15-20	17.5	0.000	1.08
3	0-5	2.5	0.189	7.35
	5-10	7.5	0.065	5.40
	10-15	12.5	0.000	2.25
	15-20	17.5	0.000	1.43

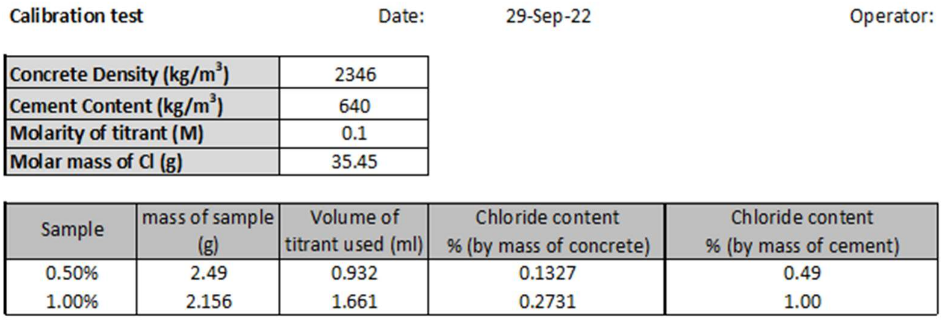
0.8 water/binder ratio average concrete chloride penetrations results

Depth (mm)	Average depth (mm)	0.8 W/C Covered		0.8 W/C Uncovered	
		Average Chloride Content		Average Chloride Content	
		% (by mass of concrete)	% (by mass of cement)	% (by mass of concrete)	% (by mass of cement)
0-5	2.5	0.353	3.55	0.632	6.35
5-10	7.5	0.042	0.42	0.393	3.95
10-15	12.5	0.024	0.24	0.310	3.12
15-20	17.5	0.002	0.02	0.234	2.35
20-25	22.5	0.000	0.00	0.171	1.72

0.45 water/binder ratio average concrete chloride penetrations results

Depth (mm)	Average depth (mm)	0.45 W/C Covered		0.45W/C Exposed	
		Average Chloride Content		Average Chloride Content	
		% (by mass of concrete)	% (by mass of cement)	% (by mass of concrete)	% (by mass of cement)
0-5	2.5	0.205	2.06	0.794	7.98
5-10	7.5	0.072	0.72	0.462	4.65
10-15	12.5	0.000	0.00	0.266	2.67
15-20	17.5	0.000	0.00	0.122	1.23

8.4.2 Titration machine calibration results



Calibration test Date: 29-Sep-22 Operator: Saarthak Surana

Concrete Density (kg/m^3)	2346
Cement Content (kg/m^3)	640
Molarity of titrant (M)	0.1
Molar mass of Cl (g)	35.45

Sample	mass of sample (g)	Volume of titrant used (ml)	Chloride content % (by mass of concrete)	Chloride content % (by mass of cement)
0.50%	2.49	0.932	0.1327	0.49
1.00%	2.156	1.661	0.2731	1.00